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Prioritizing Prescribed Fire to Protect Water Quality in the Central Sierra

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Signature Page

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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We would like to acknowledge that the CABY region is the ancestral homeland of the Miwok, Washoe, Nisenan, and Mountain Maidu tribes, and that other tribes have had connections with these lands through trade, migration routes, and other uses. Treaties signed on July 18 and September 18, 1851 forced the Das-pia, Ya-ma-do, Yol-la-mer, Wai-de-pa-can, On-o-po-ma, Mon-e-da, Wan-nuck, Nem-shaw, Be-no-pi, and Ya-cum-na peoples onto a reservation between the Bear and Yuba Rivers, and the Cu-lee, Yas-see, Lo-clum-ne, and Wo-pum-ne peoples onto a reservation along the Cosumnes River. These coercive treaties, which were never ratified and were kept secret for nearly 50 years, effectively nullifying the limited rights they were meant to convey, amount to theft of lands from indigenous communities in California at the hands of the United States government as part of the larger California Genocide (Royce, 1896). The Miwok descendants of these peoples currently reside within the CABY at the Shingle Springs and Auburn Rancherias. The rancherias of other indigenous groups including the Nisenan people were illegally terminated by the California Rancheria Termination Acts in the 1950's and 60's and have yet to be restored. We strongly encourage the Bren School, American Rivers, the US Forest Service, and all those managing lands in the CABY region and throughout California to make good-faith and respectful efforts to engage and empower local tribal partners as the original stewards of these lands through consultation before practicing burning and other forms of land stewardship. We look forward to a time when indigenous communities everywhere are restored the agency to manage their ancestral lands.

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Acronym List

CABY	Cosumnes, American, Bear, and Yuba watersheds
CARs	Critical Aquatic Refuges
CDFW	California Department of Fish & Wildlife
CLIGEN	Climate Generator
CMIP5	Coupled Model Intercomparison Project (Phase 5)
CNDDB	California Natural Diversity Data Base
CSA	Critical Source Area
CWHR	California Wildlife Habitat Relationships system
DEM	Digital Elevation Model
ERC	Energy Release Component
ERMIT	Erosion Risk Management Tool Interface
FlamMap	Fire Behavior Mapping and Analysis System (computer program)
FSim	Large Fire Simulation System (wildfire risk simulation software)
GIS	Geographic Information System
HUC	Hydrologic Unit Code
IPBN	Indigenous Peoples Burning Network
IFTDSS	Interagency Fuel Treatment Decision Support System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LANDFIRE	Landscape Fire and Resource Management Planning Tools
LCP	Landscape File (FlamMap modeling input)
MSCL	Minimum Channel Length
NID	National Inventory of Dams
OEHHA	Office of Environmental Health Hazard Assessment
PG&E	Pacific Gas & Electric
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Station
RCP	Representative Concentration Pathway
RUSLE	Revised Universal Soil Loss Equation
SSURGO	Soil Survey Geographic Database
SWAT	Soil & Water Assessment Tool
TOPAZ	Topographic Parameterization (digital landscape analysis tool)
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
WEPP	Water Erosion Prediction Project
WUI	Wildland-Urban Interface

1. Executive Summary

Forest management practices over the last century have resulted in less resilient forest ecosystems in the Sierra Nevada. Where mosaic forest structures once dominated the landscape, today's headwater forests are denser and more homogenous, making them much less resilient to wildfire, drought, and pests (McCann et al., 2020). These structural changes, coupled with climate change stressors, have made California's headwater forests more vulnerable to high-severity wildfires. Since 2010, nearly 2 million acres of the Sierra Nevada's western slope have burned, much of it at high severity (SNC, 2019).

Due to steep slopes and heavy seasonal rains, Sierra Nevada watersheds are highly susceptible to erosion after high severity wildfires. Post-fire erosion in the Sierra Nevada threatens the primary drinking water supply of over 23 million people and 60% of California's water supply overall (*California's Primary Watershed*, n.d.). In 2014, sediment and debris flows following the King Fire resulted in costly damage to water and hydropower infrastructure and demonstrated the vulnerability of the state's water infrastructure. In addition, post-fire erosion can severely damage aquatic habitat. Ash and debris increase turbidity, nutrient loading, and sediment accumulation, which is harmful to aquatic species (McCann et al., 2020).

To bolster forest resiliency and reduce the impacts of high-severity fires, California is attempting to increase the pace and scale of forest fuel reduction practices, including prescribed burning. However, insufficient funding, limited capacity, and arduous permitting for fuels reduction projects make it critical to prioritize treatments areas that will yield the greatest benefit. Several prioritization methodologies for fuel treatments exist, but many focus on the protection of homes as the primary goal. Frequently, fuel treatments are sited near places that recently experienced a wildfire due to high risk salience in these areas (Wibbenmeyer et al., 2019). However, little attention has been paid to prioritizing fuel treatments specifically for the protection of water infrastructure and aquatic ecosystems.

To help close this gap, the Forests to Faucets team developed a hydrocentric prioritization methodology that identifies locations where high post-fire sediment production coincides with high value aquatic habitat and water infrastructure, as well as areas where underresourced communities and local water quality concerns are concentrated. Our prioritization methodology consists of seven components: 1) aquatic habitat prioritization, 2) water infrastructure prioritization, 3) vulnerable communities analysis, 4) local water quality analysis, 5) burn probability analysis, 6) treatment feasibility analysis, and 7) analysis of avoided sediment loss due to fuel treatment. The subwatersheds recommended for fuel treatment constitute the intersection of the outputs from these seven components.

Our method has two phases of prioritization. In the first phase, 10-12 high priority watersheds are identified based on their habitat, infrastructure, vulnerable communities, and local water quality scores in addition to burn probability and treatment feasibility. Post-fire erosion is modeled for each high priority watershed under a pre-treatment scenario and a post-treatment scenario to assess the quantity of sediment loss that is averted by fuel treatment. In the second phase of prioritization, the watersheds identified in the initial prioritization phase are reprioritized based on avoided sediment loss due to prescribed fire in addition to burn probability, and habitat, infrastructure, vulnerable communities, and local water quality scores. The three highest ranking watersheds identified in the second phase of prioritization are recommended for treatment.

We demonstrate this methodology by prioritizing prescribed fire locations in the Cosumnes, American, Bear, and Yuba (CABY) watersheds, a region that is fire prone, ecologically rich, and a significant contributor to California’s water supply. We identified 11 high priority watersheds in first phase of prioritization and modeled fire severity and post-fire erosion on each one. In the second phase of the prioritization, we weighted components based on the priorities of our client, American Rivers. Based on our prioritization, we recommend fuel treatment in Grizzly Creek – Middle Yuba River, Little Bear Creek – Bear River, and Slate Creek watersheds to protect river ecosystems and clean water supply in the CABY region.

The result of our research is a transferable decision support tool that can be used to guide fuel treatment planning throughout the Sierra Nevada. The tool prioritizes HUC-12 watersheds where prescribed fire will most reduce wildfire impacts to high value water resources while protecting vulnerable communities. The tool provides users with the flexibility to determine the relative importance of the available benefit considerations to match their interests and the region’s specific needs. This also allows users to explore many different scenarios to assist in optimal siting for fuel treatment projects at a regional scale.

Recent state and regional efforts to increase the pace and scale of forest management are likely to increase the funding and resources available for fuel treatment in the coming years. Our methodology allows land and water managers to incorporate consideration of water resources into their fuel treatment planning to direct resources where they will most benefit ecosystems, communities and water resources.

2. Project Overview

2.1 Significance

Forests are a critical piece of California's natural water infrastructure. Headwaters forests contribute to reliable water supply and improved water quality by capturing, storing, and filtering water. However, wildfires pose a significant threat to the river ecosystems and clean water supply throughout California. After a severe wildfire, most watersheds experience increased erosion which can carry high sediment volumes along with potential pollutants to river systems, reducing water quality for both the humans that rely on these systems for drinking water and the native species that rely on riparian areas for habitat.

Over a million acres burned in California in both 2017 and 2018, the two worst fire years in state history up to that point (*Cal Fire: Statistics & Events*, 2019). In 2020, those previous records were shattered with over 4 million acres burning across the state (CalFire, 2020a). The California Water Plan identifies catastrophic wildfire as one of the critical threats to sustainable water management (O'Daly et al., 2019). Watersheds in the Sierra Nevada supply drinking water to over 23 million people and are the source of 60% of California's water supply, so when a large wildfire occurs in a Sierra watershed, its effects are felt in ecosystems and communities far beyond the fire's perimeter (SNC, 2019).

Fuel treatments, including prescribed fire and thinning, can reduce wildfire risk and improve forest health, but limited funding, staff capacity, public opinion, and arduous permitting make implementing fuel treatments a challenge (Beaty & Taylor, 2001; C. Miller & Urban, 1999). Fuel treatments are typically intended to reduce wildfire risk to communities and improve forest health; water is rarely the focus, if it is included at all. However, research suggests that fuels reduction in less than 10% of a watershed can be sufficient to significantly reduce wildfire risk to water supply (Gannon et al., 2019). In addition, there can be significant economic benefits from treatment - a study in a Central Sierra watershed found that the avoided benefits of treatment outweighed the costs at a ratio of three to one (Buckley et al., 2014). Therefore, identifying high priority areas for prescribed fire will allow forest managers to focus their limited resources on project areas that will yield the greatest benefits. While a fuel treatment prioritization focused on clean water supply has been conducted in Colorado, to our knowledge, no such prioritization has yet been done for Sierra Nevada

American Rivers is a national river-focused non-profit with a California regional office. Recognizing the significant threat posed to California's rivers by wildfire, American Rivers has begun to engage in fuels reduction efforts in the Sierra Nevada. American Rivers helped launch meadow restoration in the region by developing a rapid assessment method that helped land managers like the USFS prioritize sites for restoration. We recognize the need for a parallel means to prioritize fuels reduction to protect California's rivers and water supply. American Rivers will use this tool to identify and vet strategic projects with the most benefit to rivers and water supply with diverse land managers and stakeholders.

2.2 Objectives

- Develop a methodology to identify locations where prescribed fire will have maximum benefits to river ecosystems and clean water supply in the Sierra Nevada.

- Identify three priority subwatersheds for fuel treatment in the Cosumnes, American, Bear, and Yuba (CABY) region.
- Create white paper to inform forest and water managers about the benefits of targeted fuels management for river health and clean water supply.

2.3. Study Region

The Cosumnes, American, Bear, Yuba (CABY) region covers 4,351 square miles in the north and central Sierra Nevada (**Figure 1**) (Martin, 2020). The region is comprised of the Cosumnes, American, Bear, and Yuba river watersheds and their 12 subwatersheds (Martin, 2020). The CABY includes portions of nine different counties, including Sierra County in the north and Alpine in the south (Martin, 2020). The majority of the CABY region is privately owned, but most of the region's forested land is owned by the US Forest Service (only 45% of forested lands are privately owned) (CalFire, 2017; USGS, 2016). Other major landowners in the region include the US Bureau of Land Management, the US Bureau of Reclamation, and the State of California. CABY land ranges from 400 feet to 9,000 feet in elevation and consequently supports a diverse array of ecosystems and habitats (Martin, 2020). The CABY region includes nine habitats of special concern and 121 species of special concern (Martin, 2020). Like much of the Sierra Nevada, the CABY region is highly susceptible to wildfire. Over the past 20 years, more than 250 fires have burned in the watershed, covering more than 250,000 acres or 9% of the watershed (CalFire, 2020b). Cal Fire classifies most of the CABY region as having a high or very high fire threat (*California Fire Threat*, 2019).

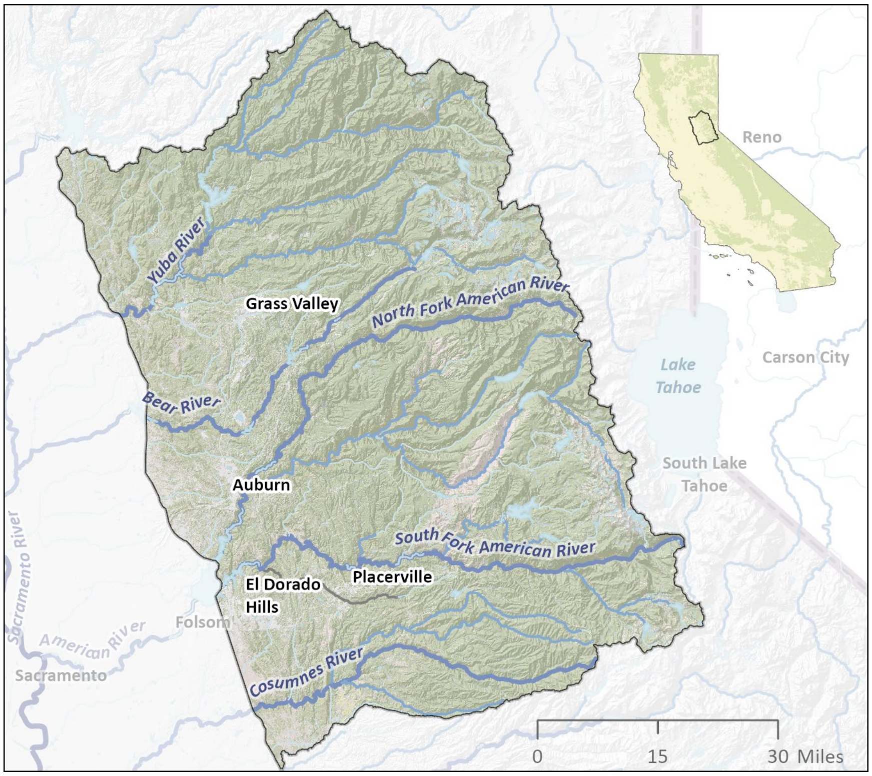

Figure 1. *Location of the CABY watershed.*

CABY watersheds make up only 2.4% of California's land area, but supply nearly 25% of the flow into the Sacramento River (CABY IRWM, 2013). The CABY watersheds supply water to several water agencies including Yuba County Water Agency, Nevada Irrigation District, Placer County Water Agency, and El Dorado Irrigation District (*CABY IRWM Project Data Management Application*, 2020). Water is often conveyed across watershed boundaries and is used for human consumption and irrigation as well as hydropower generation. The region contains at least 40 water supply reservoirs owned by regional water agencies, as well as PG&E and the Sacramento Municipal Utility District. In total, there are over 132 dams in the region, many of which are smaller than the major water supply reservoirs, and therefore at higher risk of sedimentation (U.S. Army Corps of Engineers, 2019).

The CABY region experienced the most intensive mining of the Gold Rush in the mid-1800s, with more than 6,000 documented mines in the region (Martin, 2020; USGS, 2017). The mercury pollution associated with the hydraulic mining during this period continues to impact local and downstream watersheds, posing a public health risk, especially to low-income populations that rely on mercury-contaminated fish as a food source and indigenous populations that engage in cultural fishing practices (Herr, 2020).

3. Background

3.1 State of the Forest

The Sierra Nevada mountain range extends approximately 400 miles from Tehachapi Pass in Southern California to Lassen Peak at the northern end of the state. The largely granitic mountains support a wide range of ecosystems, from chaparral-oak woodlands in the foothills to fir dominated forests at high elevations. This resource rich landscape has supported human populations for more than 10,000 years, but due to intensified human use and alteration over the past 200 years, the forests are no longer healthy. Logging, grazing, fire suppression, prolonged drought, and bark beetle infestation have left forests increasingly overgrown with millions of dead trees, putting them at high risk for catastrophic wildfire.

A Fire Adapted Landscape, Shaped by Humans

Fire is a natural part of the landscape in the Sierra Nevada. Many species native to the range require fire to flower, sprout, release seeds, or germinate (Sierra Nevada Ecosystem Project, 1996). Fire return interval varies with forest type and elevation. High elevation forests historically burned infrequently, but with high intensity (James K. Agee, 1993). Conversely, lower elevation forests, such as ponderosa pine and mixed conifer, burned more frequently but with lower intensity (J. K. Agee & Skinner, 2005).

Ethnographic accounts along with pollen and charcoal records suggest that indigenous burning practices helped maintain more open forests in the Sierra Nevada, making them less susceptible to high-severity fires (Klimaszewski-Patterson et al., 2018; Sierra Nevada Ecosystem Project, 1996). Research has also shown that California native plants may be better adapted to controlled fire than invasive species, further supporting California tribes' integral role in vegetation management (Hankins, 2013). These forests likely experienced frequent, low-intensity surface fire, which consumed litter and reduced understory density (Kilgore & Taylor, 1979). According to historical accounts, early Euro-American fire suppression was facilitated by light fuel loading (S. B Show, 1929).

Since the mid-1800s, Euro-Americans have altered the ecosystems of the Sierra Nevada through grazing, logging, mining, recreation, settlement, and consistent fire suppression (Sierra Nevada Ecosystem Project, 1996). These practices have produced forests that are denser and have more small-diameter trees than pre-settlement times (Sierra Nevada Ecosystem Project, 1996). A century of fire suppression has caused non-fire adapted species such as white fir, Douglas fir, and juniper to become more prevalent and has increased the homogeneity of the landscape (Allen et al., 2002; Beaty & Taylor, 2008). Additionally, without the disturbance of fire, surface fuel and ladder fuel loads have accumulated (Reinhardt et al., 2008; S. Stephens et al., 2009). Taken together, these changes in forest structure and composition have led to forests that are highly susceptible to large, high-severity wildfires (Sierra Nevada Ecosystem Project, 1996; S. L. Stephens et al., 2007).

Current Fire Risk

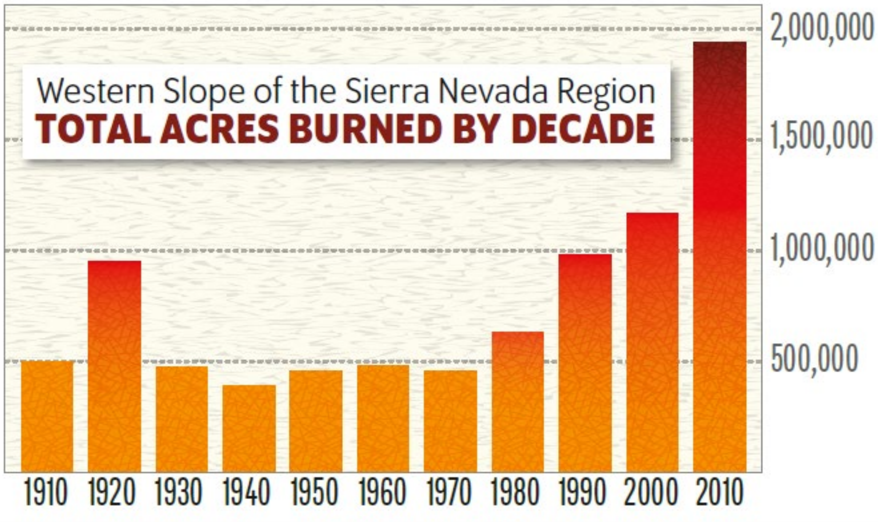

Figure 2. *Total acres burned by decade on the Western Slope of the Sierra Nevada. (Figure credit: Sierra Nevada Conservancy, 2019).*

Extended drought and climate change are compounding the already heightened wildfire risk due to decades of fire suppression. Climate change is extending fire season in the Sierra Nevada; the average wildfire season today lasts 78 days longer than it did during the 1970s (SNC, 2019). While droughts are common in the West, anthropogenic climate change is increasing the duration and severity of droughts, with the current megadrought cycle being the second driest since 800 CE (Williams et al., 2020). Drought years in the Sierra Nevada are associated with more wildfire activity and larger fires (Gill & Taylor, 2009; Westerling et al., 2003). Modern drought conditions, compounded by bark beetle infestations, have left more than 119 million dead trees in Sierra Nevada forests, which has drastically increased fuel loading (SNC, 2019). Taken together, warmer, drier weather, a longer fire season, and increased fuel loads increase the risk of catastrophic wildfire.

3.2 Water Quality Impacts of Wildfire

In the aftermath of a high severity fire, sediment yield, streamflow, peak flows, and debris flows can significantly increase, presenting risks to water supplies and aquatic habitat (Hacker, 2015). Increased water temperature and nutrient concentrations due to wildfire can also impair water quality. The extent to which wildfire affects water quality is dependent on how fire characteristics (size, frequency, intensity, timing, etc.) interact with watershed characteristics (climate, topography, soil type, vegetation type, land use, burn history, etc.) (Hacker, 2015; Malmon et al., 2007; Ranalli, 2004; Wondzell & King, 2003).

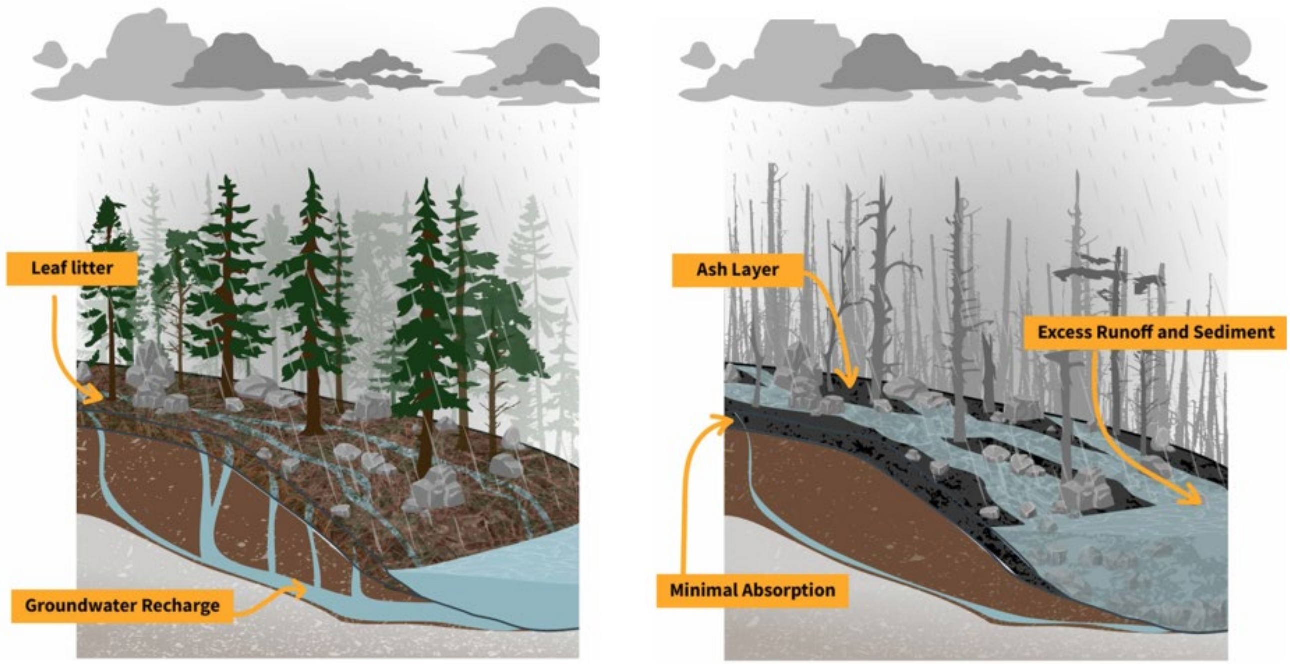

***Figure 3**. Pre- (left) and post- (right) fire hydrology. Before a fire, the forest acts as a sponge for water with vegetation intercepting rainfall and protecting the soil from erosion. When water does reach the soil, it is soaked up and slowly released, reducing the risks of rapid flooding. After a fire, these functions are altered. Rainfall can directly hit the soil surface, excess runoff can transport ash and other contaminants to streams, and soils can form a hydrophobic layer which reduces soil absorption. Figure credit: USGS, 2020.*

Changes to Water Yield

After a wildfire, water yield can increase substantially without vegetation to intercept and take up precipitation. In some cases, streamflow can increase by up to 20% following wildfire (Wine et al., 2018). This can exacerbate erosion, mobilize sediment and other contaminants into waterways, and increase the risk of debris flow, all of which threaten downstream infrastructure. During the first year after a fire, the extent to which water yield increases depends on fire severity, rainfall intensity, snowmelt, and vegetation/litter loss (Neary et al., 2003). If vegetation cover and litter are reduced by 90%, surface runoff may increase by more than 70% (Robichaud et al. 2000). Once vegetation begins to recover, evapotranspiration levels increase and the water yield begins to return to pre-fire levels (Heath et al., 2014). Increased streamflow often persists for at least 5 years after a wildfire and may take up to a decade to return to pre-fire levels (Blount et al., 2020; Hallema et al., 2018; Neary et al., 2003).

Increases in Sediment Yield

Wildfire increases erosion and sediment yield due to changes in vegatation cover and soil properties. Without vegetation intercepting rainfall on its way to the forest floor, more bare ground is exposed to precipitation and overland flow, resulting in increased erosion (Hacker, 2015; Neary et al., 2005). This is exacerbated by reduced soil infiltration and soil-water storage when the organic layer has been consumed by fire (Hacker, 2015). Intense wildfires can also create hyper-dry soils, leading to hydrophobicity which can reduce infiltration by orders of magnitude for up to five years after a fire (Abraham et al., 2017; DeBano, 2000). Water repellant soils can increase erosion from even small precipitation events (DeBano, 2000). This is particularly a problem in the West where short but intense precipitation events are common (Neary et al., 2005).

Post-fire erosion and sediment yield are also affected by local climate and topography. Short-duration, high-intensity rainfall events are responsible for transporting large amounts of sediment after a fire. In general, sediment yields are usually highest in the first year following a wildfire and can remain elevated for up to 14 years in severely burned watersheds (Neary et al., 2005). However, if a wildfire is followed by below-average precipitation, sediment delivery may be delayed. Additionally, slope is a major determinant of post-fire sediment yield, with steep terrain producing the highest sediment yield (Neary et al., 2005). Landscape and climate variability make the timing and magnitude of post-fire erosion and sediment yield difficult to predict (Neary et al., 2005).

While less common than surface erosion, debris flows are frequently the most damaging form of post-fire erosion. During a debris flow, soil, water, and rock mix into a slurry that quickly descends steep channels (Iverson, 1997). These events can cause significant changes to channel structure and threaten aquatic ecosystems and human settlemnts (K. D. Hyde et al., 2017). Like surface erosion, debris flows are most likely to occur in the first year after a wildfire, but are possible up to 10 years after a fire, especially in steep, forested areas (DeGraff et al., 2015). While models exist to predict debris flows, there is a high level of uncertainty in the results, and results are dependent on extreme storm events, making them hard to use in conjunction with surface erosion predictions (Buckley et al., 2014; K. D. Hyde et al., 2017).

Sediment erosion from severe wildfire poses a serious threat to drinking water supply and the infrastructure associated with it. Increased sediment yield can interfere with drinking water treatment and even temporarily shut down treatment plants by clogging filters and intakes (Sham et al., 2013). Suspended sediment in the water also hinders the detection of viruses and bacteria and limits effective disinfection (H. G. Smith et al., 2011). Sediment also collects in reservoirs, reducing their water storage and hydroelectric generating capacity.

Post-fire sediment impacts to water supply have proven costly to address. For example, following the King Fire in 2014, 50% of which burned at high severity, an influx of sediment into three reservoirs forced Placer County Water Agency to shut down hydroelectric operations for weeks and reduced their water storage capacity (Heller, 2018; “King Fire Poses Ongoing Watershed Challenges,” 2015). One of those reservoirs, Ralston Afterbay, has lost about half of its original storage capacity as a result of sediment from the King Fire. These impacts cost Placer County Water Agency $3-5 million in lost hydroelectric generation and $8 million in infrastructure repairs (“King Fire Poses Ongoing Watershed Challenges,” 2015). Water agencies in other regions have faced even higher costs. Denver Water has spent $26 million treating drinking water and dredging Strontia Springs Reservoir following the Buffalo Creek (1996) and Hayman (2002) wildfires. The Los Angeles County Public Works plans to spend $190

Savings for Local Water Utilities

Recent findings suggest that the avoided cost to water suppliers from fuels reduction are greater than the cost of fuel treatments themselves. An especially relevant example is the Mokelumne Avoided Cost Analysis, which occurred in the watershed just south of the CABY watershed. This assessment found that the benefits of treating the forest (including the avoided costs of sedimentation impacts to water infrastructure, structure and infrastructure loss, avoided fire suppression and cleanup, and carbon sequestration) outweighed the costs of treatment by three to one, a conservative estimate and one that does not reflect the extreme fires that have been seen in more recent years (Buckley et al., 2014).

million dredging four of its reservoirs impacted by sediment from the 2009 Station Fire.

Increased erosion and sediment delivery to waterways following wildfire also impacts stream ecosystems. In the short term, fine sediment in the water can suffocate fish, amphibians, and aquatic insects (Hacker, 2015; Malmon et al., 2007). In addition, the influx of sediment can bury fish habitat and food resources (Sedell et al., 2015). However, fish populations in burned streams can recover quickly (1-2 years), even in streams where fish were extirpated due to wildfire (Sedell et al., 2015).

Increased Concentration of Nutrients & Metals

A review of research across 153 burned watersheds and 159 fires in the western United States suggests that increased nutrient and metal concentrations are common after a wildfire. Fire can also cause changes in stream sulphates, pH, organic carbon, and chloride. Nutrients are mobilized by the combustion and volatilization of forest organic matter during a wildfire (Sham et al., 2013). Nutrient influx into waterways depends on the rate of vegetative regrowth, as revegetation leads to a decrease in nutrient runoff and erosion rates (Wittenberg et al., 2014). In addition, nutrients and metals bound to sediment particles are easily removed and transported with runoff from post-fire landscapes (Rust et al., 2018). Elevated post-fire metal concentrations were observed in 25-50% of fires (Rust et al., 2018). Little research has been conducted on the post-fire metals concentrations in areas with a history of mining. This issue if of great concern in California due to its history of hydraulic gold mining, which mobilized large concentrations of arsenic and mercury into water bodies as part of the gold extraction process.

Changes in Water Temperature

When the forest canopy burns, the previously cool, shady riparian zone is exposed to sunlight. This results in increased stream temperatures, which can reduce dissolved oxygen, shrink or fragment the habitats of native fish, and alter species composition (Gannon et al., 2019; Isaak et al., 2010). Increased stream temperatures can persist for more than 10 years depending on overstory regeneration time (Dunham et al., 2007; Isaak et al., 2010; Klose et al., 2015; Mahlum et al., 2011; Sestrich et al., 2011). While wildfire generally increases stream temperatures both during and post-fire within burned areas, wildfire smoke can

Compounding Impacts of Historical Mining

Gold brought Euro-American settlers to the Central Sierra in the mid-1800’s, and the impacts of the Gold Rush have left a lasting impact on the hillslopes and waterways of the region. Hydraulic mining, the technique of using high-pressure water jets to dislodge gold-containing sediments from hillsides, is responsible for adding over 1 billion m^3 of sediment to northern Sierra Nevada waterways between 1853 and 1884 (James, 2005). It also significantly changed stream channel morphology, affecting sedimentation in high rain events and the stability of floodplains. In some mountain valleys, extensive sand and gravel deposits persist with steep slopes more than 20 meters above the valley bottom which continue to erode and add sediment to streams (James, 2005).

Once the soil was dislodged by highly pressurized water cannons, mercury was added to extract gold from the sediments. Mercury contamination from abandoned mines and mine sediments persist throughout the region to this day and present risks to public health and wildlife (Alpers et al., 2016). It is estimated that 26 million pounds of mercury were used during the Gold Rush, with 10-30% of this being released to the rivers and ecosystems of the Sierra Nevada (Herr, 2020). From just one of thousands of abandoned mines, 100 grams of mercury are released every year to a key drinking water source (The Sierra Fund, 2015).

Wildfires are well known to release soil- and vegetation-bound mercury to the atmosphere through volatilization, but they can also release mercury to riparian systems through increased post-fire erosion (Murphy et al., 2020). Numerous studies have found increases in mercury concentrations in both sediments and fish in water bodies downstream of burned catchments (Kelly et al., 2006; Murphy et al., 2020). This is especially concerning as, in aquatic environments, elemental mercury can be converted by microbes to methylmercury, a highly toxic form that is very easily absorbed into the tissue of living organisms, including humans. With climate change, it is likely that this problem will only escalate as the rate of wildfires becomes more frequent and the severity more intense which will likely lead to increased erosion (Eagles-Smith et al., 2016).

have a cooling effect on stream temperature in unburned areas (David et al., 2018; Hitt, 2003).

3.3 Fuels Management Strategies

Treating fuel loads through prescribed fire and thinning can significantly reduce fire spread, size, and severity when implemented strategically (A. Ager & Vaillant, 2010; B. M. Collins et al., 2011). Reducing forest density through fuel treatment produces stands similar to pre-settlement conditions (**Figure 4**) (Sierra Nevada Ecosystem Project, 1996). In addition, fuel treatments can reduce wildfire suppression costs by providing improved opportunities for fire management (Thompson et al., 2014). While the typical goals of fuel treatment include reducing surface fuels, increasing height to live crown, reducing canopy continuity, and decreasing crown density to reduce the risk of wildfire, there can be significant variation in the effectiveness of treatments depending on treatment type, time since treatment, and fire weather conditions (J. K. Agee & Skinner, 2005; Peterson et al., 2005). In particular, fuel treatments may not alter fire spread or behavior under extreme fire weather conditions, which are happening more frequently due to climate change (Prichard et al., 2020).

The current pace and scale of forest management in the Sierra Nevada is insufficient to reduce the spread of severe wildfires. Studies of fuel treatments in the Sierra indicate that 20-30% of the landscape must be strategically treated to reduce wildfire spread and severity (Tubbesing et al., 2019). However, only about 16% of Sierra headwaters forests have been treated since 2010, and the pace of fuel treatment implementation has not increased (McCann & Xiong, 2021). In the CABY region, treatment scale ranges from 15% in the Yuba Watershed to 21% in the South Fork American Watershed (McCann & Xiong, 2021). According to the South Yuba River Citizens League's 2020 watershed-wide stakeholder survey, major challenges to increasing the pace and scale of forest restoration in the Sierra Nevada headwaters include: unique land ownership patterns, high percentage of lands with a wilderness-urban interface, climate change, historic mining impacts, and fire suppression policies (Thomson & Salmon, 2020). Increased funding for forest management in recent years is expected to increase the pace and scale of fuel reduction in California's headwaters forest, but given the significant backlog of forests that have yet to be treated and the need for retreatment to maintain fuel reduction benefits in treated areas, there is much more work to be done.

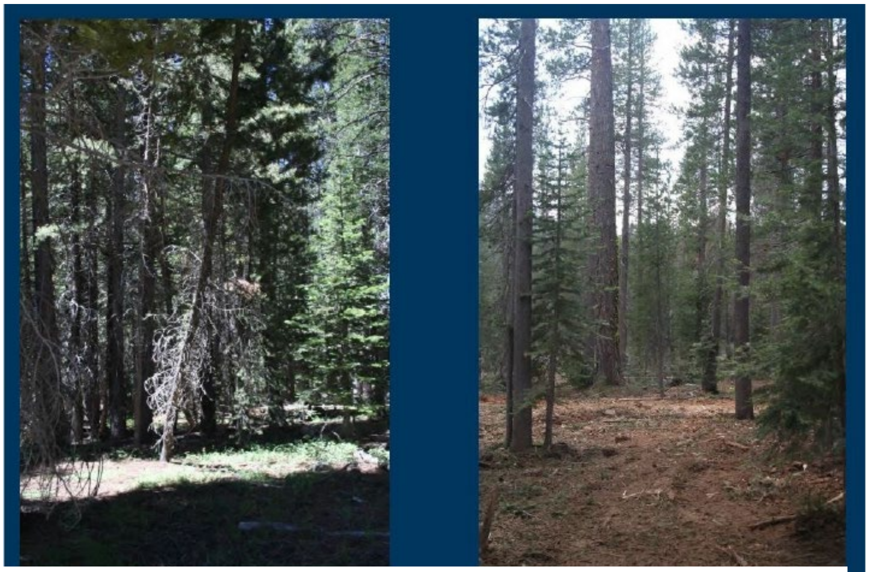

Figure 4. *Forest composition before and after fuel treatment. (Figure credit: The Nature Conservancy).*

Prescribed Fire

Prescribed fires have the ability to reduce fuel loads and restore fire as an ecosystem process. During a prescribed fire, fine fuels, duff, large woody fuels, rotten material, and other live surface and ladder fuel loads are reduced (Graham et al., 2004). One study in a Sierra mixed conifer stand found that prescribed fire reduced total fuel load by as much as 90 percent (S. Stephens & Moghaddas, 2005). Prescribed fire can also help restore heterogeneity to mixed conifer forests that have become more homogenous without regular fires (Evans et al., 2011). Estimates for the longevity of prescribed burn effects in the region range from ten to 14 years, however the benefits diminish over time due to regrowth (Graham et al., 2004; Keifer et al., 2006; Scott L. Stephens et al., 2012).

Prescribed fire is frequently the least expensive fuel treatment option available, but it comes with risks (USFS et al., 2005). The cost of prescribed fire in the Central Sierra Nevada is $490 per acre on average, but can range from $360 to $923 per acre (Hartsough et al., 2008). Traditionally, prescribed fires have been viewed as risky due to the potential to damage human infrastructure (Sierra Nevada Ecosystem Project, 1996). However, acceptance of prescribed fire has increased over time so that a majority of Westerners now support its use (McCaffrey & Olsen, 2012; Toman et al., 2014). Recent large and deadly wildfires in California have shifted community opinions from reticent to enthusiastic in many parts of the state (Barringer, 2019). Prescribed fire can be hindered by air quality restrictions, lack of funding, and lack of trained personnel (Sierra Nevada Ecosystem Project, 1996).

Thinning

For this report, thinning refers to both mechanical thinning and hand thinning. Mechanical thinning refers to the use of machines to reduce forest density. Hand thinning refers to the removal of vegetation using hand crews and chainsaws. Mechanical thinning is limited by the topography of a region, while hand thinning can occur across a greater landscape range. Mechanical thinning in the Central Sierra Nevada costs $1,040 per acre on average, but costs can range from $486 to $1,578 per acre (Hartsough et al., 2008). In some thinning scenarios, the costs of removal can be offset through the sale of the removed timber. If thinning is not paired with slash treatment, wildfire risk can increase after thinning due to the increased amount of dead vegetation and surface fuels. Common methods of slash treatment include pile burning, mastication, and slash removal. Thinning can also be paired with prescribed fire to reduce severity of prescribed burns. Some studies

Native American Cultural Burning Practices in the CABY

The CABY region is the ancestral homeland of the Miwok, Washoe, Nisenan, and Mountain Maidu tribes, and other Native American groups had connections with these lands through trade and migration routes (D. Hankins, personal communication, February 16, 2021; Native Land, 2021). Today, the Auburn and Shingle Springs Rancherias are two existing Miwok communities within the CABY.

Controlled burning holds cultural significance for many tribes in California, and this practice was an important part of stewardship and land management prior to European colonization. Burning was used for a multitude of land management objectives in both riparian and upland areas, and tribes' traditional ecological knowledge promoted the growth and regeneration of native species using low- and moderate-intensity fire (Hankins, 2013). Most tribal burning activities in the state today are constrained to private and tribal-owned land, which make up a small fraction of ancestral territory (D. Hankins, personal communication, February 16, 2021). The regulatory landscape for tribes to practice cultural burning and stewardship on public land is prohibitively complex, and highly contingent on tribal resources, shifting political interests, and jurisdiction of neighboring lands (J. Aldern, personal communication, February 4, 2021).

Growing initiatives to restore agency over cultural burning practices and land management using fire to native peoples include the Indigenous Peoples Burning Network (IPBN). This network is a cooperation between various tribes, The Nature Conservancy, and several Federal agencies. IPBN’s use of fire will also help forested lands adapt to climate change by reducing fuel loads that drive high-intensity, destructive wildfires (Huffman, 2021). In Northern California, IPBN is working with the Yurok, Hoopa, Karuk, and Klamath tribes to expand tribal involvement in fire management, and this initiative is poised to involve other tribal groups throughout the state (Huffman et al., 2019).

have found that this pairing was more effective at reducing fire hazard than either thinning or prescribed fire on their own (Hartsough et al., 2008). In addition, thinning is sometimes necessary prior to a prescribed burn to reduce the chance of the treatment becoming un-controlled.

Both manual and hand thinning can increase forest resiliency to fire in situations where prescribed fire may not be feasible or safe (such as near rural communities) (Stevens et al., 2014). However, not every thinning treatment will reduce risk of high severity fire (J. K. Agee & Skinner, 2005). If thinning removes larger trees and decreases overall stand diameter and height, fire risk can actually increase (James K. Agee, 1996).

Limitations of Fuel Treatments

While fuel treatments have been shown to reduce fire risk, they may not be effective in all locations or in all wildfire scenarios. The effects of fuel treatments on fire regime are temporary and longevity depends on the rate of regrowth, forest type, elevation, and climate. More research is needed on fuel treatment effectiveness and longevity (M. A. Finney, 2001).

Fuels Management Locations and Decision-Making

Siting of fuel treatments is a often a political process, with better-resourced communities receiving increased access to fuel treatments. The allocation of fuel treatments in California has been biased by disaster salience, with communities that were recently affected by wildfire receiving more fuels reduction treatments (Wibbenmeyer et al., 2019). This diverts resources from more at-risk communities with higher fuel loads where fire salience may be lower (S. E. Anderson et al., 2018). Additionally, available financial resources may affect a community's ability to engage in lobbying, which can motivate local fuel reductions and therefore reduce community wildfire risk (S. Anderson et al., 2020). Homeowners are often responsible for hazard mitigation on their own land, through both home site selection and site management such as thinning and/or prescribed burning. The high cost of fuels reduction activities can significantly hinder low-income people's capacities to reduce their exposure to, and recuperate from, wildfire impacts (T. W. Collins & Bolin, 2009; Morrow, 1999). Communities that are vulnerable to wildfire are considered in siting of fuel reductions projects by the US Forest Service, however this process is not transparent and may not include important socioeconomic factors that affect community wildfire resilience.

How fuel treatment locations are determined is dependent on the land owner. For example, the US Forest Service usually prioritizes fuel treatment locations based on proximity to human infrastructure, budget, fuel loading, deviation from historic fire regime, ecological objectives, site accessibility, and weather conditions. At a landscape scale, this decision-making process is decentralized and contingent upon the priorities of individual forests and their managers (A. A. Ager et al., 2013; S. E. Anderson & Anderson, 2013; M. A. Finney, 2001). Fragmented land ownership further complicates fuel treatment planning, resulting in decreased investment in fuels reduction in "checkerboard" areas (Busby et al., 2012; C. Thomas, personal communication, May 7, 2020).

Fuel Treatments in Riparian Zones

Research into the role of fire in riparian zones is limited. The analysis that has occurred indicates that historic fire return intervals were similar in riparian and upland habitats (Van de Water & North, 2010). In certain areas, like those where streams are particularly wide and/or deep or where the riparian vegetation is high in moisture, streams have been shown to be effective barriers to fire spread. Fire return intervals were likely longer in these areas (Van de Water & North, 2010). In recent years, however, watercourses have also been shown to act as channels for wind driven fire since denser biomass in the riparian zone can lead to increased fire severity under exceptionally dry conditions (North, 2012). Riparian zones can therefore either act as obstacles to fire through moist vegetation or spread fire by providing high concentrations of fuel. This introduces high variability into fire behavior in these areas. Widespread logging in the riparian zone followed by a century of fire suppression has also resulted in widespread conifer encroachment in Sierra Nevada riparian zones.

Fuel treatments in riparian areas are contrained by local, state, and federal regulations designed to protect the sensitive riparian habitat. For instance, the Tahoe National Forest is managed in accordance with the 1988 Lake Tahoe Basin Management Unit Forest Plan, which guards against introduced disturbances in riparian areas (Kattelmann & Embury, 1996). In addition, the California Department of Fish & Wildlife requires a Stream Alteration Agreement (CDFW Code Sections 1601-1603) when work is undertaken below the mean high-water mark. On a national level, the Forest and Rangeland Renewable Resources Planning Act and the National Forest Management Act (36 CFR 219.13 9(e)) prohibit management practices that “cause detrimental changes in water temperature, chemical composition, blockages to water courses, and deposits of sediment.” In addition, US Forest Service practices must minimize tree removal and land disturbing activities within 100 feet of streams and rivers to comply with Forest Practice Rules.

While fuel treatments are allowed in riparian zones, many foresters have avoided them due to potential legal challenges (Graydon et al., 2020). In recent years, treatment in riparian areas has received increased attention, but managers are still hesitant. This has led to few and relatively small treatments in the riparian zone (Stone et al., 2010). Environmental Assessments, mandated by the National Environmental Policy Act, in the CABY region have addressed fuel treatments in riparian zones to avoid the erosional impacts of high severity wildfire. While these assessments acknowledge the risks of treating in riparian areas, they determined that mitigation efforts (like not lighting prescribed fires in riparian areas, but allowing the fire to burn there) could prevent many of the potential impacts. In addition, they acknowledge that low intensity prescribed fire would be unlikely to adversely impact riparian species and might even benefit them. For instance, removing trees in riparian zones can increase basking opportunities for western pond turtles (USFS Pacific Southwest Region, 2018). Conversations with wildlife managers in the region indicate that more focused research is needed into the potential species impacts of natural and prescribed fire in the riparian zone (Chellman, 2020; Ewing et al., 2020).

3.4 Water Quality Impacts of Fuel Treatments

Fuel treatments have been shown to have insignificant effects on water quality, and any impacts tend to be short-lived. Low to moderate severity prescribed fire in montane ecosystems of the western US that was not excluded from the riparian zone has been shown to have no effect or negligible effects on stream temperature, large woody debris, fine sediment in pools, channel morphology, and erosion (R.S. Arkle & Pilliod, 2010; Bêche et al., 2005; Scott L. Stephens et al., 2004). Negligible effects on water chemistry were observed, but water chemisty parameters returned to reference levels within 3 months of treatment (Bêche et al., 2005; Scott L. Stephens et al., 2004). Furthermore, prescribed fire has been shown to have no detectable effect on macroinvertebrate communities, fish and amphibian abundance, and stream habitat characteristics, both immediately and in the 3 years following a prescribed burn (R.S. Arkle & Pilliod, 2010). Erosion and surface rillling was found to be minimal after low and moderate severity prescribed fires since these treatments retain enough organic matter to trap sediment (Berg & Azuma, 2010; Harrison et al., 2016).

Forest thinning by mechanical harvest has the potential to compact soils, thereby decreasing infiltration and increasing erosion. In practice, studies have shown that the impacts of thinning are minimal and can be mitigated. For instance, in the Tahoe basin, mechanical thinning had little effect on overall soil compaction and erosion rates on forested slopes (Hatchett et al., 2006). Best practices such as mastication and planting native vegetation cover have been found to substantially reduce erosion at thinned sites (Hatchett et al., 2006). Mechanical fuel treatments, including thinning, mastication, and pile burning, were not found to increase the percentage of bare soil or to induce post-treatment rillling (Berg & Azuma, 2010). As with prescribed fire, sediment yields were lowest at masticated sites where bare ground was minimized (Harrison et al., 2016). Prescribed fire and mechanical harvest can also be used in concert to reduce wildfire risk. The combination of both treatment types was found to have small impacts on nutrient loads in overland runoff in a Sierra Nevada watershed (Loupe et al., 2009).

4. Fuel Treatment Prioritization Landscape

Fuel treatments are needed across the entirety of the CABY landscape in order to return healthy forest dynamics and foster climate resilience (Manley, 2020). However, limitations in funding, staff capacity, and resources have severely constrained progress toward this goal. The process of prioritizing locations to reduce fuels can help managers direct limited resources toward the most vulnerable areas. Given the varied stakeholders involved in fuel treatment planning, there are a diverse set of goals when it comes to fuel treatment prioritizations. We conducted a series of stakeholder interviews in order to learn more about the priorities of the stakeholders in the CABY region.

4.1 Approach to Interviews

Over 30 individual stakeholders from conservation organizations, water agencies, government (federal and state) agencies, and consulting organizations were interviewed in our interview process. Many of the individuals contacted were recommended by our client, American Rivers, or other interveiwees, and are not exhaustive of all stakeholders in the region. Interviews were conducted via phone or video and were limited to one hour at most. In some cases, interviewees were contacted with follow-up questions.

4.2 Current Fuel Treatment Prioritization Landscape

Within the past 10 to 20 years, the approach to fuel treatment prioritization has changed dramatically due to increased fire risk and increased attention on reducing that risk. Prior to the recent emphasis on increasing fuel treatments, fuel treatments were implemented opportunistically when funding and landowner willingness allowed for treatment implementation. Increasing calls from stakeholders (including the California Forest Management Task Force, the Nature Conservancy, and the Public Policy Institute of California) to increase the pace and scale of treatments is starting to shift fuel treatment design from a property-scale to a landscape-scale, with prioritization needed to effectively utilize limited

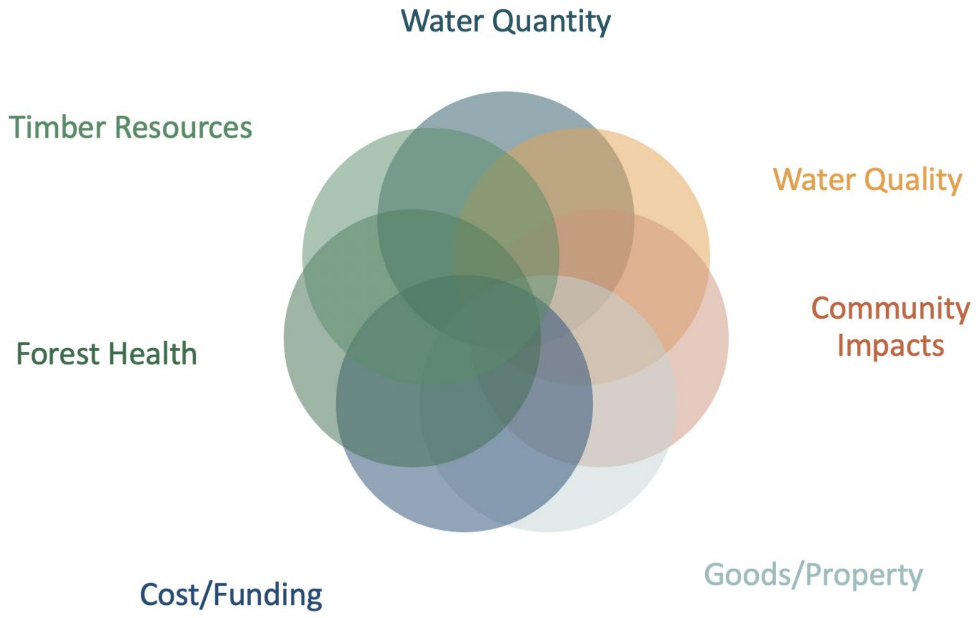

Figure 5. *Key priorities to locating fuel reduction practices as identified from stakeholder interviews.*

resources (California Forest Management Task Force & California Department of Water Resources, 2021; Kelsey et al., 2017; McCann & Xiong, 2021).

From our interviews, we distilled seven generally accepted fuel reduction priorities that could be used in regional assessments: cost of/funding for treatment, risk to goods and property, negative impacts to local communities (e.g. increased smoke), timber resources available from treatment, benefits to forest health, increased water quantity, and avoided water quality impacts (illustrated in **Figure 5)**. Examples of efforts that include these elements in prioritization include work by the US Forest Service, The Nature Conservancy, and the Tahoe Central Sierra Initiative.

The US Forest Service has conducted wildfire risk assessments across much of the state, which they use to help inform fuel treatment prioritization. As part of this process, they identify highly valued resources and assets that are at risk from wildfire. The values included in these risk assessments include human habitation and infrastructure, sensitive terrestrial species, and erosion risk (at a relatively coarse scale) (Helmbrecht et al., 2015). In the Nature Conservancy's prioritization, watersheds across the Sierra Nevada were ranked based upon risk to human communities, biodiversity value (which included aquatic species), and departure from historic fire densities (Kelsey et al., 2017).

Finally, the Tahoe Central Sierras Initiative, is working on an ongoing fuel treatment prioritization project across an area that covers much of the CABY region. This effort has established 10 pillars of restoration to inform regional prioritization of fuel reduction resources in order to steward a fire resilient landscape with changing climate conditions (Manley, 2020; *Tahoe-Central Sierra Initiative | Tahoe Conservancy*, 2020). The 10 pillars are: forest resilience, fire dynamics, biodiversity, carbon sequestration, wetland integrity, water security, air quality, economic diversity, fire-adapted communities, and social and cultural wellbeing. In the context of this assessment, water security is focused on water quantity more so than water quality.

Water Agency Approach to Prioritization

Due to the potentially devastating impacts of wildfire on water infrastructure, water agencies and irrigation districts in the CABY region are invested in fuels reduction prioritization and are already conducting fuels reduction in their watersheds. For example, the Nevada Irrigation District, which serves over 27,000 customers (*Water Service*, 2020), has been conducting forest maintenance and watershed conservation on forest lands surrounding their reservoirs and critical infrastructure. However, land ownership and economics limit the amount of land a water agency can treat on its own (King & Townsend, 2020).

Partnerships between water agencies, non-profit organizations, and the US Forest Service have been effective at treating large areas for multiple benefits, including water quality. Two notable examples include the North Yuba Partnership and the French Meadows Project. The North Yuba Partnership, a collaboration between Yuba Water Agency and several other groups, is conducting fuel treatments on nearly 300,000 acres of the North Yuba watershed to protect water resources from wildfire impacts. The work is funded by the Forest Resilience Bond, which connects external investors with secure, long-term bonds to fund fuel reduction work that will be paid back by a collective of beneficiaries. The French Meadows Project was prompted by the 2014 King Fire, which resulted in millions of dollars of remediation costs and lost revenue to Placer County Water Agency. The project aims to reduce fuels and improve forest health on over 19,000 acres of forested land through thinning, prescribed burning, mastication, reforestation, and meadow restoration. In addition, the project will research the connection between fuels reduction and water balance.

While the goal of both of these projects is to protect water quality, water quality was not a factor in treatment area selection. For instance, in the North Yuba Partnership, treatment locations were selected by the US Forest Service for overall forest health without considering the impacts to water quality in the selection process.

4.3 Gaps in Current Prioritizations

While water agencies are already actively engaged in fuel treatments and are considering the impacts to water resources, they are limited in their scope and many of the larger prioritization efforts are not actively considering the impacts to water resources. When water quality is included in prioritization efforts, it is treated as an additional benefit of fuel treatment but is not primary goal of the effort.

In addition, water agencies are focused on the water quality impacts of fuel treatments to human water infrastructure, but little to no focus is given on prioritizing fuel treatments to avoid water quality impacts to sensitive riparian habitats. Our modeling efforts, described in the next section, aim to fill this gap by prioritizing fuel treatment locations based upon water quality impacts to both human infrastructure and riparian health on a landscape scale.

5. Prioritizing Fuel Treatment for Water Quality Benefits

To identify locations for fuel treatments to maximize benefits to water quality, we created a hydrocentric prioritization methodology that identifies locations where high post-fire sediment production coincides with high priority aquatic habitat and/or water infrastructure. We demonstrate this methodology by prioritizing fuel treatment locations in the CABY watersheds, a region that is fire prone, ecologically rich, and a significant contributor to California's water supply.

Several similar assessments have demonstrated the effectiveness of targeted fuel reductions to protect water resources from wildfire impacts and provided a framework on which we built our prioritization methodology. Kreitler et al. (2019) developed a cost-effective fuel treatment planning algorithm that incorporated cost as well as ecosystem benefits including avoided sediment loss. This methodology was demonstrated for the Deschutes National Forest in Oregon, where it was shown that fuel treatments can be a cost-effective measure to avoid sediment-related impacts from wildfire. Similarly, Gannon et al. (2019) developed a fuel treatment optimization model to minimize risk to water supplies, which was tested in two major watersheds in Colorado. The results indicated that targeted fuels reduction in 10% of watershed can significantly increase water quality. Finally, the *Mokelumne Avoided Cost Analysis* determined that strategically reducing hazardous fuels would reduce probability, extent, and intensity of fire resulting in cost savings and multiple benefits to watershed stakeholders. The *Mokelumne Avoided Cost Analysis* was especially influential in the development of our methodology since the Upper Mokelumne watershed is contiguous with the southern border of the Cosumnes watershed (Buckley et al., 2014). Together, these studies show support for the notion that strategically placed fuel treatments are an effective means of protecting water resources. In addition, avoided sediment loss due to fuel treatment was at the core of all three studies and was determined by modelling pre- and post-treatment fire behavior and sediment production (**Figure 6**). We incorporated this same approach into our methodology.

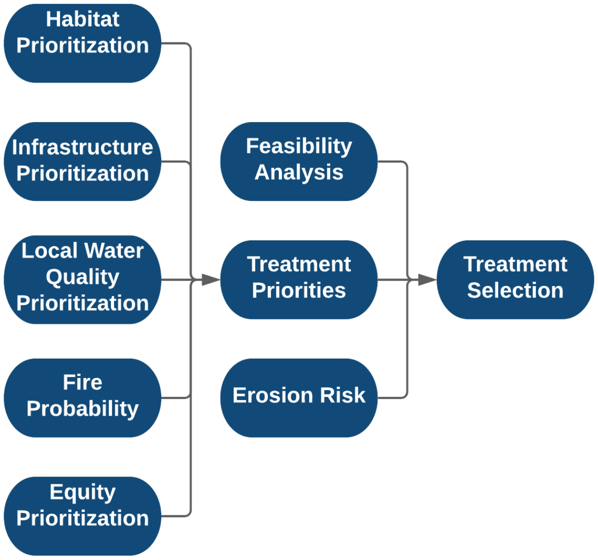

Figure 6. *Draft conceptual model of fuel treatment prioritization for water quality benefits.*

Our prioritization methodology is composed of six distinct steps: 1) identifying areas with high value habitat and infrastructure that are vulnerable to wildfire impacts, 2) identifying areas where local water quality issues and under-resourced communities are concentrated, 3) identifying areas where wildfires are most likely to occur, 4) identifying which subwatersheds of the CABY watershed are feasible to treat with prescribed fire, 5) identifying expected burn severity in the event of a wildfire in high priority subwatersheds through fire modeling, and 6) modeling the amount of erosion and sediment transport avoided by placing fuel treatment practices on the landscape in high priority watersheds. The final planning units used for fuel treatment recommendations constitute the intersections of the outputs from these six analyses.

Figure 7. *Avoided sediment loss was calculated by subtracting the post-fire erosion with fuel treatment from the post-fire erosion without fuel treatment.*

High value areas for aquatic species and clean water supply were identified through separate habitat and water infrastructure prioritizations (described in detail below), and burn probability was prioritized within the region. High priority fuel treatment locations were identified as the intersection of high burn probability, high value habitat, high water infrastructure value, and areas where local water issues and under-resourced communities are concentrated. Feasibility analysis was used to refine fuel treatment locations, with watersheds where less than 25% of the land area is treatable excluded from the remainder of the analysis. By this process, eleven high value, treatable subwatersheds were identified.

To model the avoided sediment loss for the selected high priority watersheds, fire severity modeling was completed and used as an input in erosion modeling. Due to time and modeling constraints, we were only able to model fire behavior under pre-treatment conditions. Based on past research, it was assumed that fuel treatment would reduce fire severity by one class (Omi & Martinson, 2010; Hugh D. Safford et al., 2009; Tubbesing et al., 2019). Post-fire erosion was modeled in each selected watershed under pre- and post-treatment burn severity scenarios and the outputs were used to calculate the avoided sediment loss resulting from fuel treatment. Final treatment recommendations were determined by incorporating avoided sediment loss into the prioritization schema.

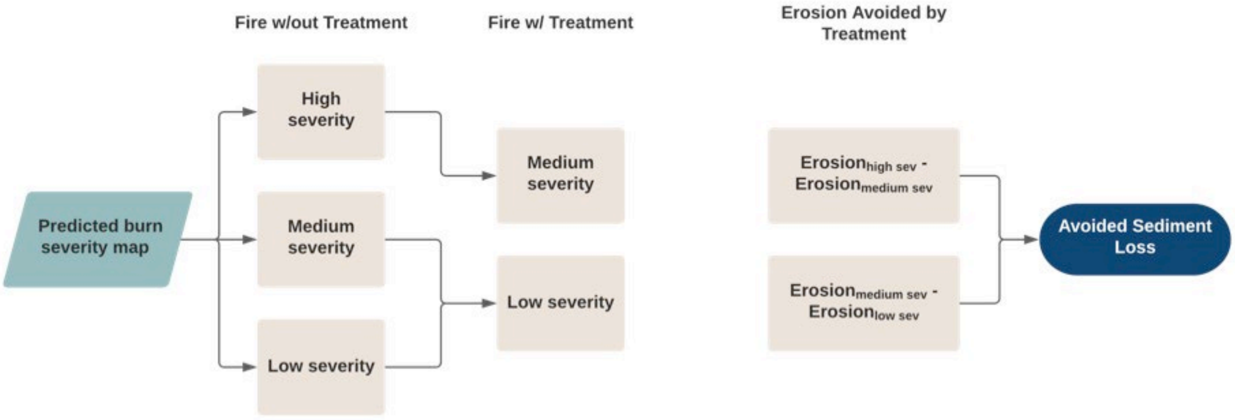

Figure 8. *Process for calculating avoided sediment loss using predicted burn severity before treatment.*

Our methodology relies on the assumption that fuel treatment will reduce fire severity, which is robustly supported by the scientific literature. While there is some variability, prescribed fire is generally acknowledged to reduce fire severity within the treatment footprint (Fernandes, 2015). Studies in California mixed conifer forests have found that burn severity was much lower in areas that were treated compared to untreated stands for up to 9 years after treatment (H. D. Safford et al., 2012). An analysis of 12 wildfires in yellow pine and mixed conifer forests in California concluded that removing surface fuels significantly reduces fire severity even under extreme weather conditions (H. D. Safford et al., 2012). The reduction in fire severity due to fuel treatment has also been confirmed by studies that modeled fire severity prior to treatment and compared model results with actual post-treatment burn severities (Robert S. Arkle et al., 2012).

5.1 Habitat Prioritization

While fire historically occurred in riparian areas and was beneficial to riparian species, the larger and more severe fires that are common today pose substantial risk to riparian species. Following a severe wildfire, increased erosion and sediment delivery to waterways can reduce suitable spawning habitat for fish, and can suffocate fish, amphibians, and aquatic insects (Hacker, 2015; Malmon et al., 2007; Wondzell & King, 2003). Debris flows and post-fire flooding can radically change aquatic communities through scouring stream substrates and removing most stream organisms (Bixby et al., 2015). Provided that connectivity exists to remaining populations, species have been shown to recover quickly (Bixby et al., 2015). However, this may not be the case for sensitive species with limited habitats (Bixby et al., 2015).

There are several riparian threatened, endangered, or species of special concern in the CABY region that may be at risk from wildfire induced erosion. Potentially at-risk species include California red-legged frog (*Rana draytonii*), Foothill yellow-legged frog (*Rana boylii*), Sierra Nevada yellow-legged frog (*Rana sierrae*), Yosemite toad (*Anaxyrus canorus*), western pond turtle (*Emys marmorata*), Pacific lamprey (*Entosphenus tridentatus*), hardhead (*Mylopharodon conocephalus*), riffle sculpin (*Cottus gulosus*), and California floater (freshwater mussel) (*Anodonta californiensis*) (CDFW, 2020; USFS, 2013). While lower intensity fires (like prescribed fire) are not likely to harm these species, high severity fires could significantly alter habitat and adversely impact these species (USFS Pacific Southwest Region, 2018).

Table 1. *Riparian species of interest and their special species status (federal or state listing or other listing).*

Species	Status
California red-legged frog (*Rana draytonii*)	Federally Threatened CDFW Species of Special Concern
Foothill yellow-legged frog (*Rana boylii*)	California Endangered
Sierra Nevada yellow-legged frog (*Rana sierrae*)	Federally Endangered California Threatened
Yosemite toad (*Anaxyrus canorus*)	Federally Threatened CDFW Species of Special Concern
Western pond turtle (*Emys marmorata*)	CDFW Species of Special Concern
Pacific lamprey (*Entosphenus tridentatus*)	CDFW Species of Special Concern
Hardhead (*Mylopharodon conocephalus*)	CDFW Species of Special Concern
Riffle sculpin (*Cottus gulosus*)	CDFW Species of Special Concern
California floater (*Anodonta californiensis*)	US Forest Service - Sensitive

Given these risks, we decided to prioritize portions of the watershed with high quality riparian habitat. Given a lack of universal information on habitat quality throughout the region, sensitive species richness and river alteration were used as proxy values.

Sensitive Species Richness

Eight sensitive riparian species were selected for the analysis based upon a literature review, confirmation with the California Natural Diversity Database (CNDDB), and conversations with species experts (CDFW, 2020; Chellman, 2020; Ewing et al., 2020; USFS, 2013). All species listed in **Table 3** were included with the exception of the California floater (*Anodonta californiensis*), a freshwater mussel, since there was insufficient data.

A variety of datasets were used to represent likely habitat for the identified species. Range data was available for the three fish species from PISCES at the HUC-12 watershed scale. Predicted habitat data for the four amphibians and one reptile was available from the California Wildlife Habitat Relationship dataset, which takes into account existing range datasets and known species locations to predict likely habitat locations. Finally, the analysis incorporated US Fish and Wildlife Service Critical Habitat locations and US Forest Service Critical Aquatic Refuge (CAR) locations for California red-legged frog and Sierra Nevada yellow-legged frog. Under these federal designations, these locations have been identified as critical to the preservation of the species. To ensure that the full area under designation was captured in the abundance dataset, the critical habitat and CAR layers were merged with the predicted habitat layers for each species.

The final species richness layer was calculated by summing raster versions of each of the species layers and clipping this to a 30-meter buffer from the streams in the region. Clipping the species layer to the streams layer was done since the habitat impacts of post-fire erosion will likely be most severe in the stream riparian areas. Given this strategy, the results of this analysis would be improved by having a more detailed fish habitat layer since many of the streams within the fish range may or may not be suitable habitat for each fish species.

River Alteration

To expand our habitat priorities beyond areas with a high sensitive riparian species richness, we also developed a score based upon the ”naturalness” of the streams. This score was designed to capture high quality habitat for both sensitive and non-sensitive species. The Center for American Progress’s Disappearing Rivers dataset was used to capture the amount of human impact and thus the amount of naturalness of rivers and streams. The Disappearing Rivers dataset assigns a percent human alteration to stream segments across the Western United States based upon impacts to the streams themselves (such as dams or other fragmentation) and the floodplains that surround them. To develop the final river alteration layer, we assigned a value from 1 to 5 to the rivers and streams in the CABY based upon their river alteration percent, with stream segments that had been altered the least receiving the highest score.

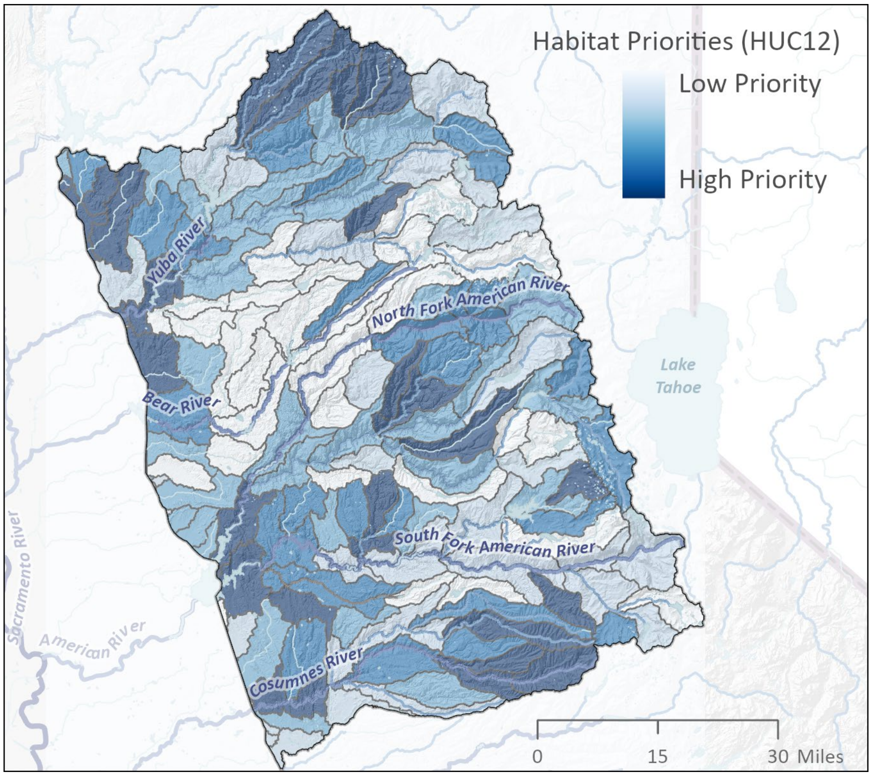

Figure 9. Habitat priorities depicted at the HUC-12 watershed scale for the CABY region. Dark colors represent areas of higher priority.

To calculate our final habitat priorities, we summed the river alteration and riparian species richness layers, equally weighting both components. These priorities were then aggregated to the HUC-12 watershed level by calculating the mean value for each watershed and then rescaling these values from 0 to 5 (Figure 9).

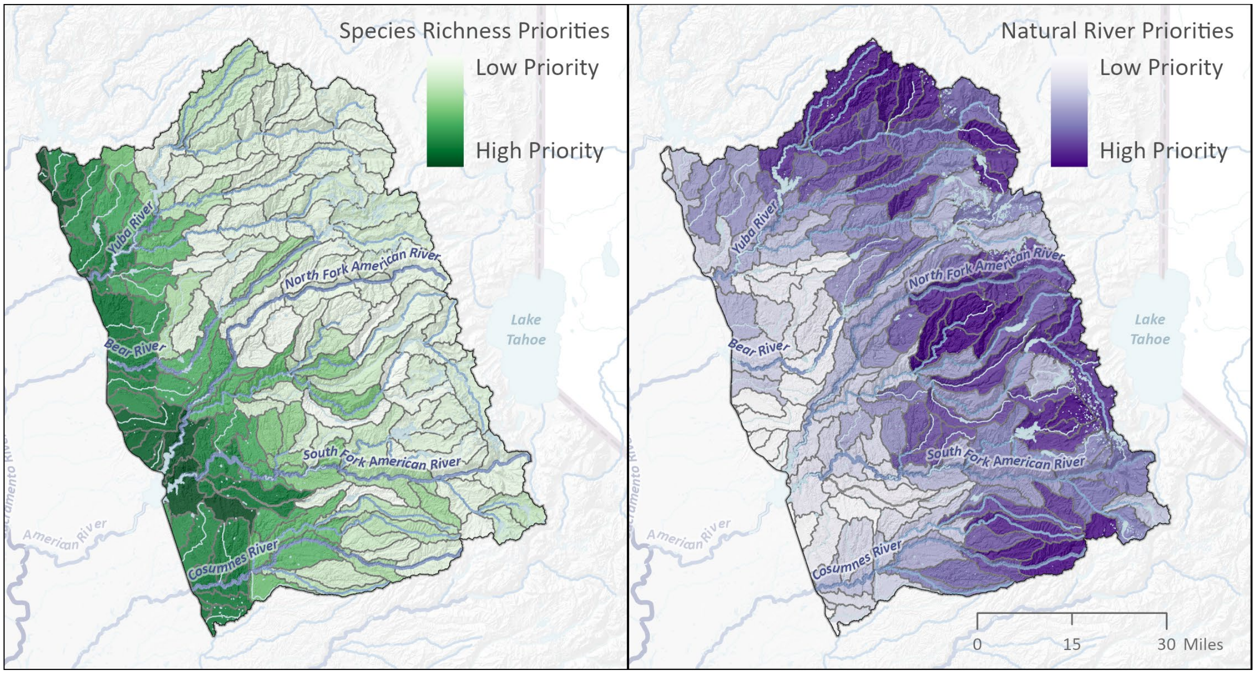

Figure 10. *Habitat priorities separated into species richness priorities and natural river priorities. Dark colors represent areas of higher priority.*

If you separate the river alteration and riparian species richness scores, and assess each component individually, the results show clear geographic preferences for low- (riparian species richness) and high- (land alteration) elevations (**Figure 10**). This makes sense given what the base layers are for each of these components. In general, the riparian species richness score prioritizes low elevations since many of the sensitive riparian species are only found at lower elevations. Meanwhile, the river alteration score prioritizes the higher elevation regions since they tend to be further away from human development. While we have evenly weighted these two components, the final tool output will be designed so that users can weight these components according to their priorities.

5.2 Infrastructure Prioritization

Watersheds were prioritized based on the importance and vulnerability of the water infrastructure contained within them. Five factors were used to prioritize watersheds for infrastructure: 1) reservoir importance for water supply, 2) hydropower generating capacity, 3) percent of reservoir capacity remaining, 4) water conveyance infrastructure, and 5) system vulnerability. The approach used to provide a relative score for each of these factors is explained in more detail below.

1) Reservoir importance for water supply: Dam and reservoir data was obtained from the National Inventory of Dams and the California Jurisdictional Dams database. Reservoirs in the CABY region are owned and operated by a wide range of entities including federal agencies, state agencies, municipalities, public utilities, private companies, and individuals. Dams owned by private companies and individuals were excluded from this analysis because they do not contribute to the water supply of the general population.

Interviews with water agency staff were used to develop a matrix that assigns each reservoir a score based on its capacity in acre-feet and its elevation (**Table 2**). Mid-elevation, regulatory reservoirs are the highest priority to protect since these reservoirs allow agencies to control water supply and regulate environmental flows. The matrix gives greater weight to smaller reservoirs at mid elevations to distinguish between regulatory and storage reservoirs, and because they are more vulnerable to sedimentation than larger reservoirs. High and low elevation storage reservoirs are considered lower priority because their or location make them less vulnerable to wildfire. At high and low elevations, the matrix gives greater weight to larger reservoirs due to their increased water storage capacity.

Table 2. *Reservoir value scoring matrix. Smaller reservoirs at mid-elevations are prioritized.*

	<20,000 AF	20,000 AF – 75,000 AF	>75,000 AF
1,000 ft - 4,000 ft	2	1	0.5
< 1,000 ft or > 4,000 ft	0.25	0.5	0.5

2) Hydropower generating capacity: Hydropower is a critical source of revenue for water agencies, but sediment from wildfires can damage hydroelectric equipment and reduce hydroelectric generating capacity (Davis, 2020; *Wildfire Impacts on the Electricity Sector*, 2018). Powerplant data was obtained from the US Energy Information Administration. Powerplants owned by private companies were excluded because the revenue generated from them does not help fund public water supply. Each watershed received a score from 0 to 5 based on the amount of power in megawatts generated annually by the hydroelectric powerplants contained within it (**Table 3**).

3) Remaining capacity: Reservoir capacity decreases over time as sediment is deposited from upstream. As the amount of available storage decreases, so does the utility of the reservoir. As a result, reservoirs with reduced capacity are especially vulnerable to post-fire sedimentation. To reflect this, the percent of reservoir capacity remaining was included as an indicator of reservoir vulnerability.

The 3W reservoir sedimentation model created by Toby Minear and Matt Kondolf was used to estimate percent of initial reservoir capacity remaining in 2020. The 3W model is a coupled spreadsheet model that iteratively calculates reservoir sediment yield based on a regional sediment yield rate, drainage area, and reservoir capacity (Minear & Kondolf, 2009). The model accounts for sediment trapping by upstream reservoirs and changes in reservoir trap efficiency over time. The regional sediment yield rate, equivalent to the median sediment yield rate of 19 surveyed reservoirs in the Sierra Nevada, was calculated by Minear and Kondolf (2009). Reservoirs were given a score from 0 to 5 based on their percent capacity remaining, with 5 being the least and 0 being the most capacity remaining (**Table 3**). Each watershed received a score corresponding to the sum of its reservoirs' scores normalized by the number reservoirs in the watershed.

4) Conveyance infrastructure: Water conveyance infrastructure including canals and pipes can be damaged by fire and post-fire sediment and debris (King & Townsend, 2020; McCann et al., 2020). Canal and pipeline data was obtained from the USGS National Hydrography Database. In order to capture only conveyance infrastructure (whose purpose is to transport raw water from storage reservoirs to regulatory reservoirs and treatment plants) as opposed to distribution infrastructure (whose purpose is to transport water from treatment plants and regulatory reservoirs to customers), canals and pipelines were excluded if their midpoint was below an elevation of 3,000 feet. Each watershed received a score from 0 to 5 based on total length of conveyance infrastructure contained within it (**Table 3**).

5) Vulnerable systems score: The first four components of the infrastructure prioritization tend to upweight watersheds where larger water agencies operate. However, smaller water agencies are more vulnerable to wildfire impacts. Small water systems consisting of just one or two reservoirs are less resilient to wildfire since their systems have fewer sources of redundancy and avenues to adapt if one or more components were critically impaired by fire or post-fire sediment. Furthermore, it is significantly more difficult for water providers with fewer, more dispersed service connections to pay for projects to keep the water system functional, including needed fuel reduction activities. The watersheds that smaller agencies source their water from are therefore in greater need of assistance to manage wildfire risk.

Reservoirs were assigned a vulnerable system score based on characteristics of the agency that owns it. Reservoirs belonging to agencies with fewer than three reservoirs and less than 60,000 acre-feet of total reservoir storage received one point. One additional point was awarded to reservoirs owned by agencies with fewer than ten households per square mile. Reservoirs belonging to agencies that do not meet either of these criteria received a score of 0. Each watershed received a score corresponding to the sum of its reservoirs' scores.

Table 3. *Scoring criteria for infrastructure prioritization.*

	0	1	2	3	4	5	Weight
Reservoir Value Score	Sum of reservoir scores within the watershed						**0.5**
Publicly owned hydropower generating capacity (MW)	0	<50k	50k-150k	150k-300k	300k- 1 million	>1,000,000	**0.3**
% reservoir capacity remaining	90-100%	80-90%	70-80%	60-70%	50-60%	<50%	**0.1**
Total length of conveyance (km)	0	< 1	< 5	< 15	< 25	< 50	**0.1**
Vulnerable system score	Sum of vulnerable system scores within the watershed						**1**

Each factor in the prioritization was assigned a weight, which was based on conversations with water agency staff, to yield an overall infrastructure score. However, the model allows future users to weight categories based on the priorities in their region of interest. Overall score was calculated for each watershed by multiplying the score for each category by its assigned weight and summing the results. This score was then rescaled to a 0 to 5 scale.

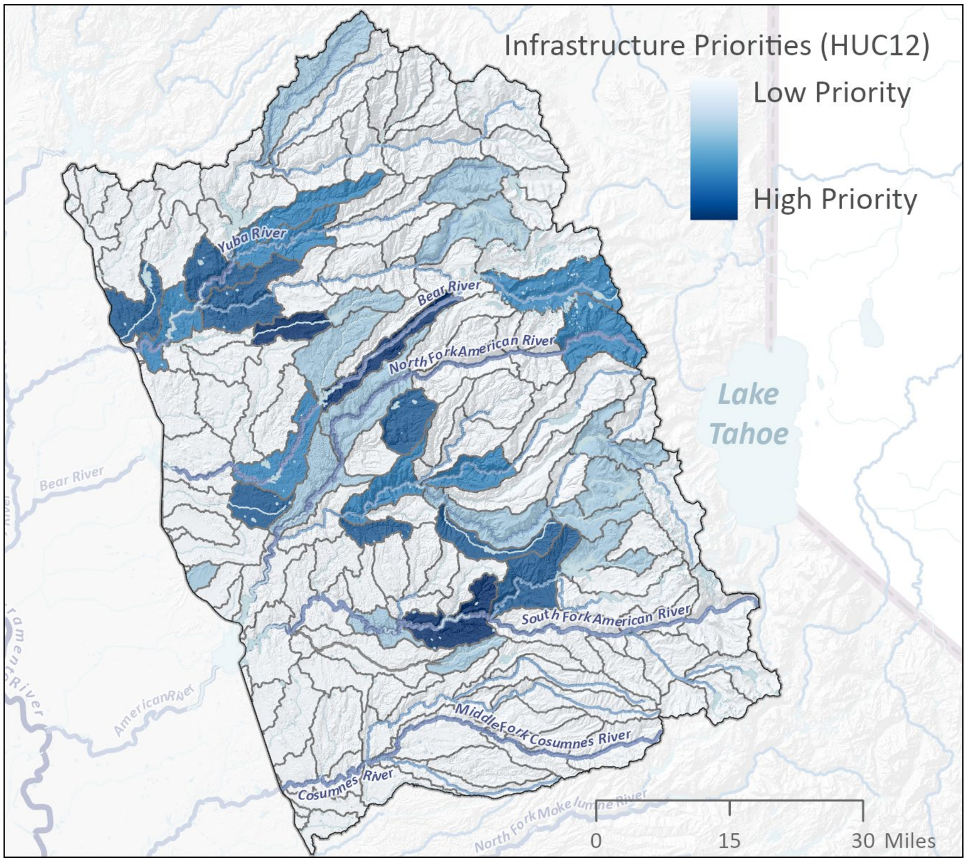

Figure 11. *Infrastructure prioritization score by HUC-12 subwatershed across the CABY watershed.*

5.3 Local Water Quality Prioritization

Every region has its own history of land use and alteration which can create unique water quality challenges that could be exacerbated by wildfire. Within the CABY region, mercury-laden sediments that resulted from historic hydraulic mining are a local water quality concern critical to fuel reduction prioritizations. We developed a specific prioritization related to mining to address this local water quality issue. When this tool is applied to other regions, an evaluation of local water quality concerns should be conducted. If additional water quality concerns are revealed that could be mitigated by fuel reduction treatments and sufficient data is available, we recommend a similar prioritization be conducted.

In the CABY region, abandoned hydraulic mine sites deposit high levels of mercury contaminated sediment into rivers and streams (Curtis et al., 2005; James et al., 2019). The Bear River, South Yuba River, and Deer Creek are all highly influenced by hydraulic mining sediment (Alpers et al., 2016). For example, Malakoff Diggins State Park contains one of the largest historic hydraulic gold mines in California from which chronic erosion resulted in a state water quality 303(d) listing of surrounding streams for sediment, mercury, copper, and zinc (*Waste Discharge Requirements for the State of California Department of Parks and Recreation*, 2017). As sedimentation from hydraulic mine sites continues long after mining has ceased, it is critical to identify areas affected by historical gold mining operations to mitigate impacts and reduce sedimentation (James et al., 2019).

This prioritization will identify watersheds that contain streams impacted by high sedimentation from hydraulic mining pits by evaluating the area of hydraulic mining pits in each HUC-12 watershed. This method assumes a similar sedimentation rate among all hydraulic mining pits since erosion data is not available from these hydraulic mining pits.

A USGS dataset of boundary location polygons for 167 hydraulic mine pits located in northern California was utilized to quantify the location and size of hydraulic mine pits in the HUC-12 watersheds. The dataset was compiled from three sources: Topographically Occurring Mine Symbols (TOMS) database produced by the California Department of Conservation (2001), Yeend (1974), and on-screen digitizing, using current (2015) satellite imagery (Orlando, 2016).

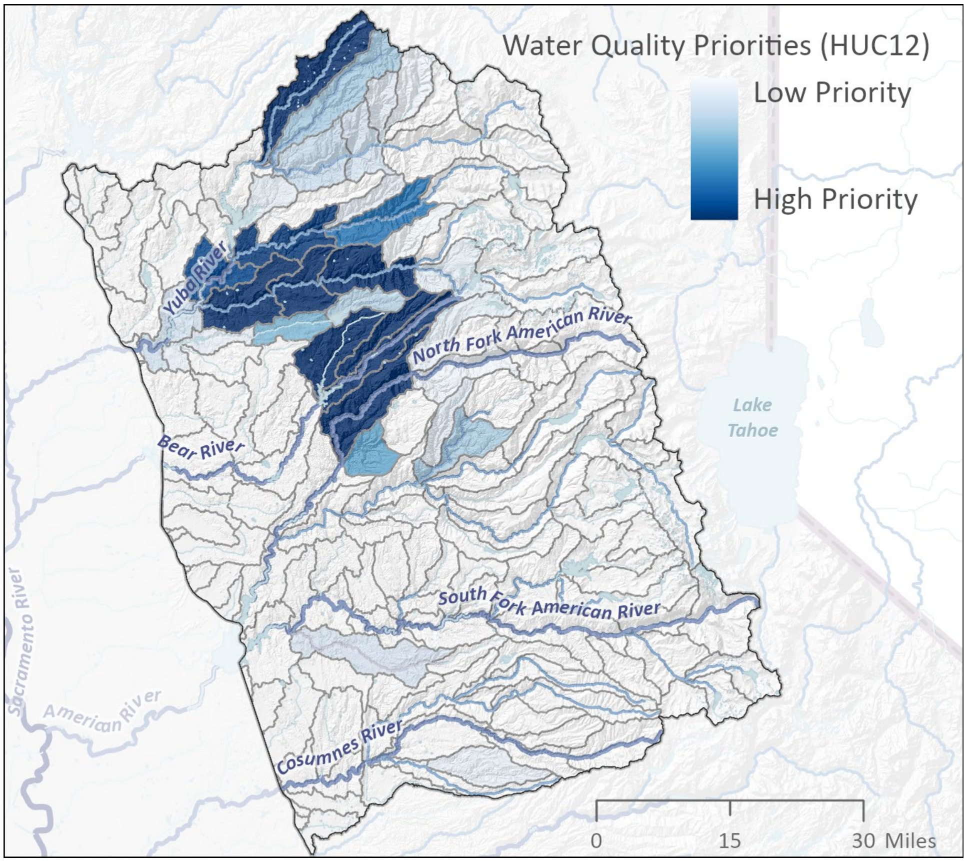

Figure 12. Water quality priorities related to historic hydraulic mining by HUC-12 watershed across the CABY watershed.

The amount of land area dedicated to hydraulic mine pits in each HUC-12 was summed for each watershed and then rescaled from 0 to 5 (**Figure 12**). Many watersheds received a score of zero since they did not contain any hydraulic mines. Within the CABY region there are 41,395 km^2 of identified hydraulic mining pits. The mean area of mining pits per HUC-12 is 233 km^2, with the highest coverage being 5,729 km^2.

There is most likely variation in released sediment related to mine age and whether the site has been remediated. Additional data on the location of debris dams (areas with high concentrations of hydraulic mining sediment), mine age, and individual mine sedimentation rates would enhance this analysis. A comprehensive inventory of abandoned mine features in California has not been completed and not all abandoned mines have been identified as physical or environmental hazards or been prioritized for remediation (The Sierra Fund, 2015).

5.4 Equity Prioritization

Disaster management often encompasses the physical hazard component and neglects the social vulnerability component (B. E. Flanagan et al., 2011). By incorporating equity into fuel reductions prioritizations this tool can be used to direct resources toward supporting communities that have fewer resources to adapt to wildfire impacts. Our objective is to define areas within the CABY watershed that would be disproportionately impacted by wildfire impacts to available water quantity and quality. The community capacity and socioeconomic status assessments done by the CABY Integrated Regional Water Management reveal that many communities within the watershed and the Sierra Nevada region face challenges related to a combination of poverty, low population density, and decaying infrastructure (Kusel et al., 2020). This equity prioritization combines data on population density, race, and income to support decision-makers in identifying communities vulnerable to wildfire impacts to local water supplies.

Population Characteristics

Population characteristics are important indicators of successful long-term recovery after a disaster. Low-income communities, racial and ethnic minorities, children and the elderly, differently able individuals, and residents of mobile homes are more vulnerable at all stages of a disaster (B. E. Flanagan et al., 2011). These socioeconomic characteristics often co-occur (Morrow, 1999). Davies et al. (2018) and Flanagan et al. (2011) both incorporate demographic, housing and transportation, language and education, and socioeconomic data into an adaptability score, illustrated in **Figure 13** (I. P. Davies et al., 2018; B. E. Flanagan et al., 2011). Many of the socioeconomic characteristics analyzed in these studies exhibit related trends and individual differences in disaster outcomes can be difficult to differentiate (S. Anderson, 2021; S. Anderson et al., 2020; I. Davies, 2021). Relationships between race, income, and disaster outcomes are well documented. In particular, median household income and the proportion of non-white individuals in a community are key contributing factors to post-disaster outcomes (S. Anderson et al., 2020; I. P. Davies et al., 2018; Morrow, 1999).

Figure 13. *This wildfire vulnerability framework reflects both the potential of wildfire and the adaptive capacity of a census tract. Source: Davies et al., 2018.*

Our equity prioritization methods are based on Davies et al. (2018) and Flanagan et al. (2011) and utilize statistics on race (non-white individuals) and median household income by census tract from the 2019 US Census American Community Survey data. This data is utilized to quantify an equity score that reflects the likelihood a community would readily rebound from wildfire impacts. The number of non-white individuals and median household income per census tract was individually ranked amongst all census tracts from 1-100. This was done in RStudio using the tidycensus package and by creating a percent rank function, illustrated in **Figure 14** Equation 1. For each census tract, the rank of median household income is subtracted from the rank of non-white inhabitants. The equity score includes a population density multiplier to ameliorate any bias from sparsely populated census tracts which may have a high percent rank (**Figure 14** - Equation 2).

Eq. 1 Percent Rank Equation

Percent Rank = rank(x)/sum(x)

Eq. 2 Equity Score Function

Equity Score = Population Density * Percent Rank (sum of non-white people per census tract)) + (1-Percent Rank (median household income))

Figure 14*. Equations utilized in our equity prioritization. Percent Rank function from Davies et al. (2018).*

Population Density

Census tracts can span multiple subwatersheds and population density varies greatly within them (*Boundaries of Census Block Group Disadvantaged Communities 2018 (MapServer)*, n.d.). In the CABY region, higher elevation subwatersheds overlap with large census tracts that contain small populations. To address this issue, a 2010 population density raster from USGS multiplied by the percent rank raster (Falcone, 2016). By using population density data at a 60-meter resolution, a close approximation of the continuous population density is attained and mitigates the modifiable areal unit problem (Cressie, 1996; Langford & Unwin, 1994). Once the population density and percent rank are multiplied, the subwatersheds are reclassified to a score of 0 to 5 with all unpopulated subwatersheds receiving a score of zero (**Figure 15**).

Uncertainty

One limitation is the rapidly changing composition of some small-area populations in the intercensal years. Since data from 2010 was utilized to represent population density in the CABY region, any geographic shifts in population density between 2010 and the present were not captured. In the CABY region low-density areas house communities of particularly vulnerable individuals. Any error in approximating population density may result in overlooking these critical groups. Groundtruthing this data by consulting local planning groups is recommended (Kusel et al., 2020).

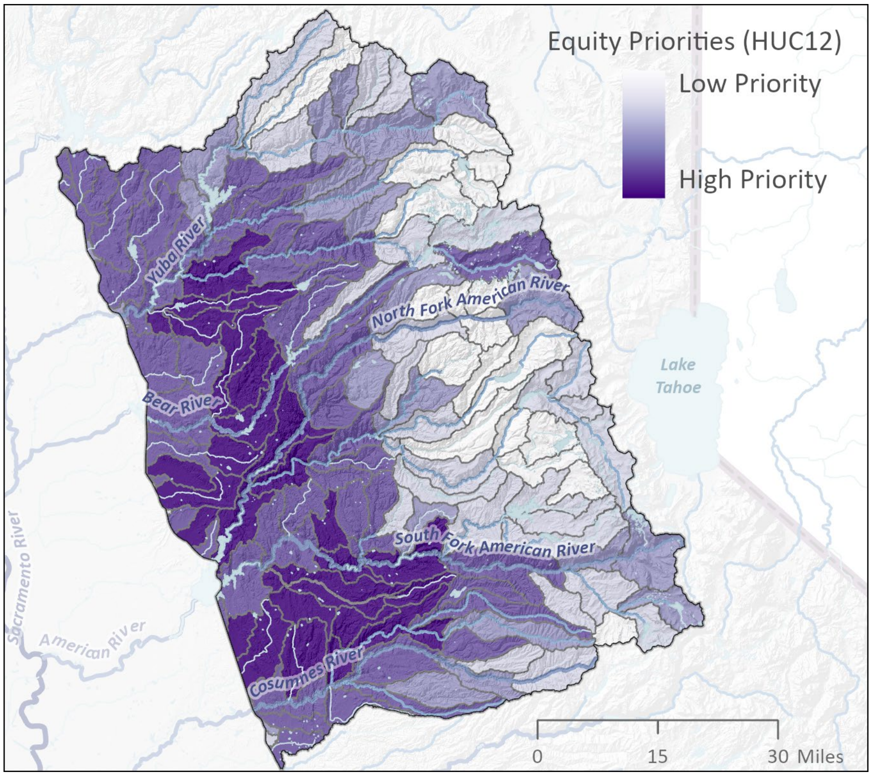

Figure 15. *Results of the equity prioritization at the HUC-12 watershed across the CABY region.*

5.5 Burn Probability Prioritization

Watersheds were also prioritized on the likelihood that a fire would burn within them. While the other prioritizations were focused on the areas that are vulnerable to the impacts of fire, this prioritization looks at where fires are most likely to occur. A recently revised national dataset developed for the US Forest Service was used to quantify annual burn probability (Scott et al., 2020). This dataset was developed using the Large Fire Simulation System (FSim) to model fire behavior across thousands of possible fire seasons, reflective of vegetation conditions in 2014. The revised dataset underwent an upsampling process in order to bring the original national dataset from its relatively course resolution of 270m up to the native 30m resolution of LANDFIRE’s vegetation data. This finer resolution allows for better assessment of wildfire likelihood on a more localized scale, such as that of a subwatershed. While this model has an inherent degree of error and uncertainty, it was the most accurate and recent analysis that was available at the time of this report. FSim remains the most widely used program in the US for wildfire risk analysis and is relied upon by federal and state agencies as well as the private insurance industry. Additionally, previous model validations have shown simulated burn probabilities generated using FSim compared reasonably well to historical data, with historic trends in burn probability and fire size distributions captured in most fire planning units studied (M. A. Finney et al., 2011).

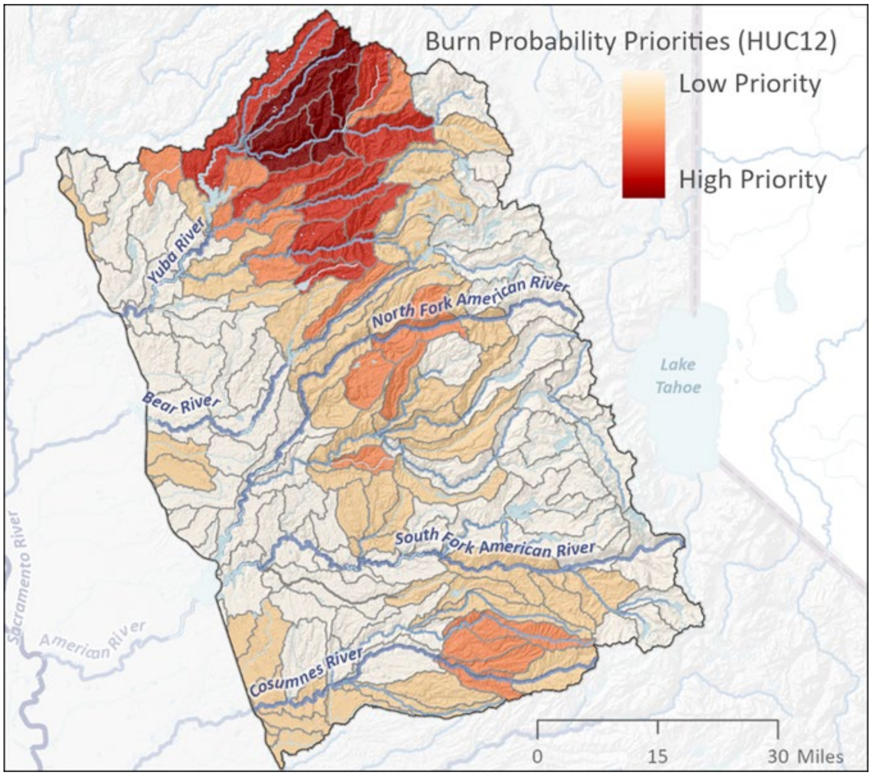

Figure 16. Burn probability priorities by HUC-12 watershed across the CABY region.

For the CABY region, annual burn probability ranged from 0% to 2.8%. These values were averaged across each HUC-12 watershed and then scaled from 1-5 to determine the burn probability priorities for the region (**Figure 16**). While the base burn probability values may intuitively seem low, these values represent the burn probability of each individual raster cell for any given year. This probability will accumulate over time, meaning that the probability that the landscape will burn in the next decade is higher than is represented by these values.

5.6 Feasibility Analysis

The next step of our analysis was to determine where fuel treatments were possible within the CABY watershed. Based upon literature reviews and interviews with stakeholders in the region, we identified several key feasibility factors that determine where prescribed fire could be implemented on the landscape. These factors were broadly categorized as societal constraints, regulatory constraints, physical constraints, and organizational constraints (See **Figure 17**). Given that spatial data was only available for the physical constraints, this became the focus of our analysis.

Our assessment was highly influenced by a North et al. 2015 analysis of mechanized treatment locations in the Sierra Nevada (North et al., 2015). While that analysis focused on mechanized treatment, many of the same principles apply to our focus of prescribed fire. Using that study as a guide, and adding additional variables that were relevant to prescribed fire, we identified six key factors to identify where fuel treatments were feasible in the watershed: 1) appropriate land cover, 2) proximity to the wildland urban interface, 3) existing fuel treatment locations, 4) recent fire history, 5) proximity to high voltage power lines, and 6) accessibility by roads to treatment area. These six factors are described in detail below:

1) Appropriate Land Cover: North et al. 2015 focused their treatment feasibility assessment on forested areas and excluded non-forested areas. While treating in other vegetation types may be needed, we mimicked this design and identified non-forested areas as not feasible for treatment (agricultural, barren, developed, open water, snow-covered, grassland, shrubland, and exotic herbaceous vegetation as identified in LANDFIRE's 2016 vegetation dataset).

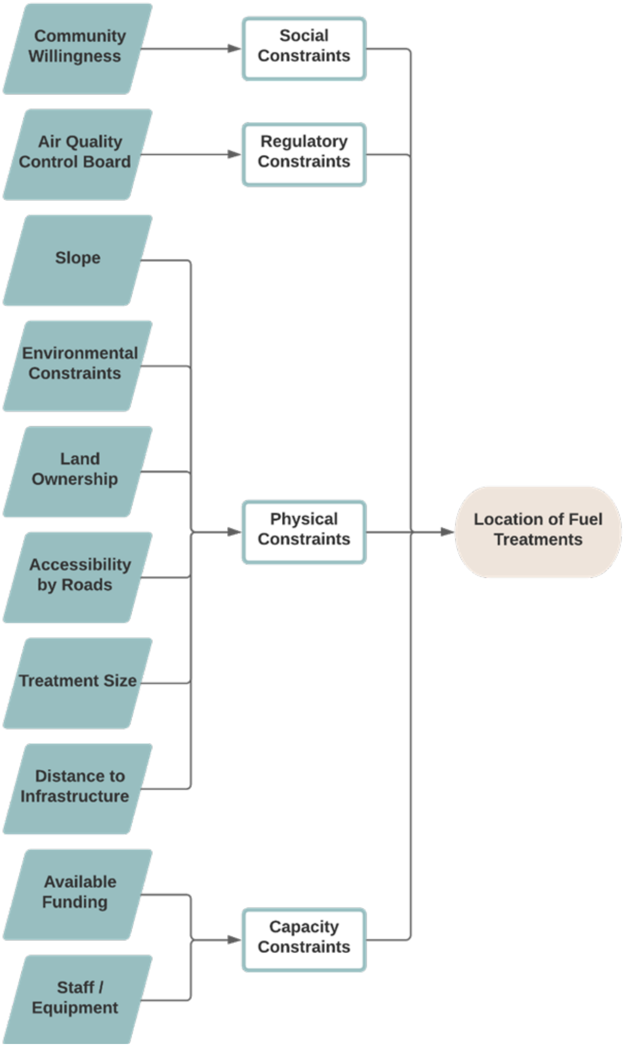

Figure 17. *Factors that effect the feasibility and placement of prescribed fire as a fuel reduction treatment.*

2) Proximity to the Wildland Urban Interface (WUI): Historically, there has been opposition to implementing prescribed fire in the WUI due to the risk to human lives and infrastructure if fire managers lost control of a prescribed fire. While this attitude is shifting, we chose to exclude treatment in the WUI out of an abundance of caution. We used the University of Wisconsin-Madison Silvis Lab 2010 WUI as the removed area.

3) Existing Fuel Treatment Locations: Since resources for fuel treatments are limited, it is unlikely that you would re-treat an area that had been recently treated, therefore we removed all known fuel treatment locations in the region. Our literature review indicated that prescribed fire normally has a lifespan of 7-10 years in the region (Scott L. Stephens et al., 2012; Vaillant et al., 2013; Yocom, 2013), therefore we removed from our treatment area all treatments that had occurred in past 5 years (assuming that a new treatment would not be implemented for a couple years due to organizational needs). In addition, we assumed that clear-cuts would behave similarly to prescribed fire, and thus excluded them from needing future treatment as well. We did not exclude other mechanical thinning types from treatment since they have a much more variable lifespan. Mechanical thinning has been shown not to reduce surface fuels, the most important component of reducing fire hazard, until after 7 years, and mechanical thinning followed by prescribed fire is recommended to produce a forest condition that is highly resistant to wildfire (Scott L. Stephens et al., 2012; Yocom, 2013).

4) Recent Fire History: Recent fire footprints were eliminated from the treatable area for the same reason as recent fuel treatments - recent fires would have already removed most of the surface fuels that could lead to a high intensify fire. Given that wildfires tend to burn at a higher severity than prescribed burns, we extended the timeframe and excluded treatment from all fires that had taken place since 2010 using the CalFire fire history dataset.

5) Proximity to High Voltage Power Lines: Personal communication with prescribed fire managers indicated that prescribed fire would not take place under high voltage power lines due to potential safety hazards (S. Graydon, personal communication, July 8, 2020). Given this, we eliminated treatment from a 200-foot buffer around all high voltage power lines.

6) Accessibility by Roads to Treatment Area: Prescribed fire treatment cannot take place where fire crews and land managers are unable to access the area due to the need to ignite and manage the treatment. However, our literature review and interviews did not indicate that there was a specific distance from roads that would be unreasonable to apply a treatment (S. Graydon, personal communication, July 8, 2020). Therefore, we used the USFS Inventoried Roadless Areas as an approximation of where treatment was unlikely due to accessibility issues.

Each of these factors was converted to a raster, projected to the proper coordinate system, and merged together to identify the areas within the CABY watershed which would be feasible and infeasible for treatment (**Figure 18**). We concluded that approximately 44% of the CABY watershed was not feasible for treatment (1, 222,000 acres). This feasibility layer was then overlayed on top of the HUC-12 watersheds used in the habitat, infrastructure, and local water quality assessments to constrain analysis of fire behavior and post-fire erosion risk. Any subwatershed where more than 75% of the area was infeasible for treatment was excluded from the erosion risk analysis.

There are a number of other factors that could have been included in this analysis, but were ignored due to the focus of our project. These include treatment in riparian areas, treatment in sensitive species habitats, and maximum slope of treatment zone. These factors were excluded for the following reasons:

- **Riparian Areas:** As detailed in the Background, wildfires in riparian zones can be beneficial to riparian health. Historically these areas have been excluded from treatment due to the sensitive habitat and concerns about erosion from mechanical treatments, but given that our focus is on prescribed fire we chose to include them due to the potential benefits.
- **Sensitive Species Habitats:** Our literature review indicated that sensitive riparian species see no adverse effects from prescribed fire and that in general, prescribed burns can be timed appropriately to avoid impacts to avian species (US Fish & Wildlife Service, 2014). Given this, any

consideration of sensitive species should be included in the treatment design plan, but was not appropriate to include in this prioritization.

- **Maximum Slope:** We could not find a maximum recommended slope for prescribed fire in our literature review.

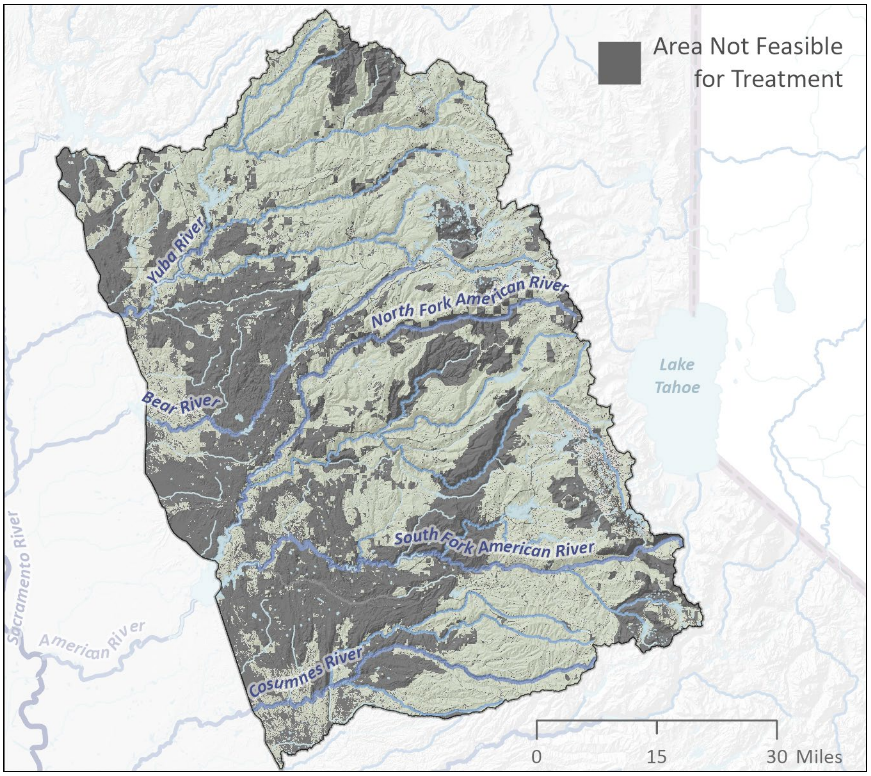

Figure 18. *Output of feasibility analysis in the CABY watershed.*

In addition, we acknowledge that mechanical thinning would likely be needed prior to prescribed fire in many portions of the watershed. We chose not to consider this as a feasibility constraint given that in some areas this would not be necessary, but would recommend consulting Malcolm North et al.'s mechanical treatment constraints layer when designing a treatment.

5.7 Treatment Priorities

Habitat, infrastructure, local water quality, and equity priorities along with burn probability were used to identify high priority HUC-12 watersheds to be evaluated for fire severity risk and post-fire erosion potential. Priority score was equivalent to the weighted sum of the five components. We weighted the components equally (weight = 0.2), but future users of this methodology could choose to assign different weights according to their priorities. Finally, any watersheds that were less than 25% feasible to treat were excluded. The watersheds with the top five priority scores were selected for further analysis.

Equally weighting the components tends to identify areas where the scores of multiple components tend to be high. However, doing so fails to capture areas that are a high priority for one component but not others. To account for this, we compared the top five scoring watersheds with the highest ranked watersheds by habitat, infrastructure, and local water quality. For each of these, the two highest ranked watersheds that were not already included in the overall top five were selected for erosion analysis. The burn probability and equity scores are not tied to water quality in and of themselves, so additional watersheds were not selected from these components. Overall, this process yielded 11 subwatersheds for further analysis: five from the equally weighted prioritization and six additional watersheds with high habitat, infrastructure, or local water quality value (**Figure 19** & **Table 4**).

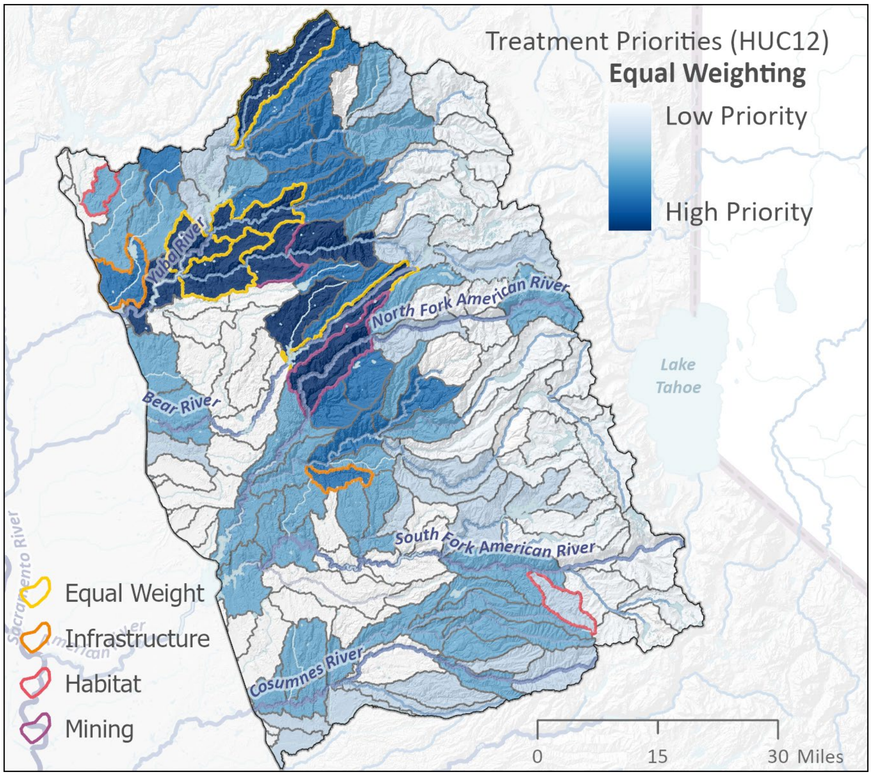

__Figure 19.__ Treatment priorities across the CABY region based upon equal weighting of the sub-components. Watersheds chosen for fire and erosion modeling are highlighted with the color representing the scenario that they were chosen from.

Table 4. *HUC-12 watersheds that were selected for fire and erosion modeling with the score from the even weight scenario and the scenario selected from.*

HUC-12 Name	Score: Even Weight	Scenario Selected
Canyon Creek	231	Infrastructure
Alder Creek	141	Habitat
Little Bear Creek-Bear River	355	Equal Weight
Rocky Honcut Creek	175	Habitat
Lower Dry Creek	233	Infrastructure
Dobbins Creek-Yuba River	325	Equal Weight
Grizzly Creek-Middle Yuba River	319	Equal Weight
Shady Creek-South Yuba River	347	Equal Weight
Slate Creek	327	Equal Weight
Rock Creek-South Yuba River	277	Mining
Indian Creek-North Fork American River	290	Mining

5.8 Fire Severity Risk

The degree to which post-fire erosion impacts occur is largely related to wildfire severity; soil erosion following severe wildfire can be up to three orders of magnitude greater than before fire (Elliot, 2013). Therefore, identifying how the risk of high-severity fire varies spatially across the landscape is necessary to better predict the degree and extent of soil erodibility following fire within the CABY region. Utilizing fire models allows us to analyze potential fire behavior characteristics and use the outputs from the model to approximate the spatial distribution of soil burn severity across the CABY. Accurate fire behavior prediction remains a challenging objective to achieve due to the spatial and temporal variability of fire and its environmental covariates. However, the development of fire models with higher accuracy and resolution is an area of active research in both public and private sectors. The biggest advantage of using fire models to generate burn severity inputs for erosion modeling is the ability to easily and efficiently swap in new model results as conditions on the ground change or more accurate fire prediction datasets become available in the future.

Wildfire severity modeling was conducted using the Interagency Fuels Treatment Decision Support System (IFTDSS), a web-based software and data integration framework that organizes fire and fuels software applications into a single online application (Drury et al., 2016). Within IFTDSS, landscape fire behavior is driven by FlamMap, a commonly used spatial fire behavior model that computes potential fire behavior characteristics such as rate of spread, flame length, and fireline intensity for every landscape pixel under constant weather and fuel moisture conditions (M. Finney, 2006). Fire behavior outputs for this analysis were acquired by running FlamMap's Basic Landscape Fire Behavior mode under 97th percentile weather and fuel conditions over ten "firescape" regions, two for each of the five major (HUC-8) watersheds in the CABY region (**Figure 20**). Fuel and weather data for 97th percentile conditions are automatically parameterized within IFTDSS for an area of interest, allowing for quick and efficient modeling of "worst-case" fire behavior throughout the West. Modeling under these target conditions is important because it helps to predict the maximum fire-severity potential for any given location and to infer where a reduction in fire severity would have the biggest impact on minimizing erosion risk.

Modern fire suppression efforts are highly effective under all but the most extreme weather conditions, which typically create the largest fires. Approximately 3% of fires are responsible for 97% of the area burned (Calkin et al., 2014). These fires tend to burn under high winds with very low fuel moistures, producing high spread rates and intensities. Effective fuel treatments must be designed with these fires and conditions in mind as there is little benefit to underestimating these target conditions, especially as climate change spurs more extreme and erratic weather patterns. The final product of fire modeling in this analysis is a burn severity raster representing the spatial distribution of fire severity across the entire CABY. This data serves as a baseline for modeling erosion under pre- and post-fuel treatment scenarios using the Water Erosion Prediction Project (WEPP) erosion model.

Fire Model Landscape Generation

Basic Landscape Fire Behavior analysis in FlamMap is deterministic — the same inputs will always yield the same outputs. Fire behavior is calculated independently for each pixel and only models fire behavior that occurs at the head of a fire as it moves across the landscape. This analysis requires a virtual landscape within FlamMap on which to simulate burning and estimate wildfire intensity. The fire modeling landscape is a set of gridded raster data layers known as a landscape (LCP) file and includes: slope, aspect, available fuel (“fuel model”), canopy cover, stand height, canopy base height and canopy bulk density. LCP files can be downloaded from the LANDFIRE database website or generated using the Lanscape Evaluation Tool within IFTDSS. The CABY LCP file in this analysis has a pixel resolution of 30 meters, representing approximately 0.22 acres. The LCP was generated using the LANDFIRE 2016 dataset and includes the 40 Scott and Burgan Fuel Model as the fire behavior fuel model and Scott and Reinhardt (2001) as the crown fire behavior model. LANDFIRE 2016 was chosen as it is the most up to date fire modeling dataset from LANDFIRE representing 2016 ground conditions. Where a disturbance occurred between 2010 and 2016, LCP files have been revised to expected 2019 or 2020 vegetation conditions. The 40 Scott and Burgan Fire Behavior Fuel Model was selected as this set contains more fuel models in every fuel type (grass, shrub, timber, slash) compared to Anderson's set of 13, improving on the accuracy of modeled fire behavior. The Scott and Reinhardt (2001) Crown Fire Model significantly predicts more crown fire activity compared to the Finney method which is important when modeling worst-case fire behavior scenarios.

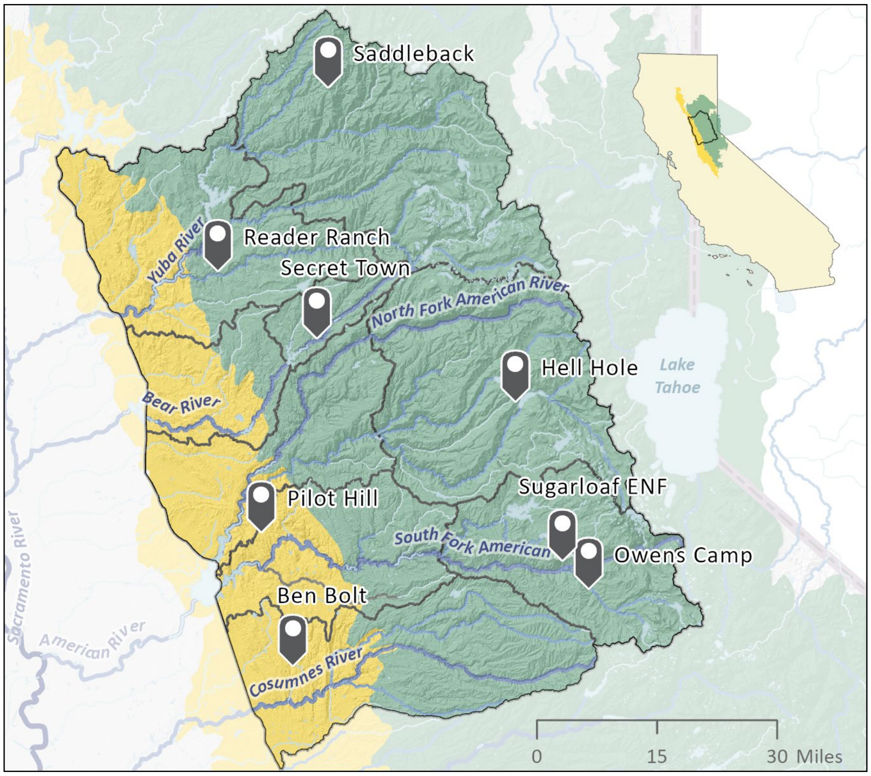

Figure 20. Pyromes, fire zones, and RAWS climate stations used in fire modeling. The Northern Sierra pyrome is depicted in green and the Northern Sierran Foothills & Tuscan Flows pyrome is depicted in yellow.

Weather and Climate Inputs

Weather and fuel moisture data needed to run FlamMap were based on weather records from eight Remote Automated Weather (RAWS) stations (**Figure 20**), a network of weather stations monitored by the National Interagency Fire Center to observe potential wildfire conditions (Zachariassen et al., 2003). Stations were selected in each model run based on their horizontal and vertical proximity to the geographical center of each firescape and whether they possessed the requisite weather data history to run the model effectively. Once a RAWS station was selected, the 97th percentile 20-ft wind speed, wind direction, foliar moisture content, and 1-hr, 10-hr, 100-hr, live herbaceous, and live woody fuel moistures during peak fire season were pulled from the stations weather history data.

Conditioning of fuels is a way to adjust initial dead fuel moisture values to capture variation in local site conditions before a fire model run. Conditioning in this analysis was especially important as the CABY region contains significant topographic and canopy variation resulting in a diversity of fine fuel moistures due to slope, aspect, canopy cover, and their subsequent impacts on solar radiation, wind, and precipitation penetration through the canopy. Fuels in this analysis were conditioned under a classified weather stream using date ranges that represent near-maximum or "extreme" conditions within either the Northern Sierra, or Northern Sierran Foothills and Tuscan Flows pyromes (Short et al., 2020)(**Figure 20**). Pyromes represent areas with similar fire characteristics which are determined by the fire regime (frequency, intensity, size, season, type, and extent), vegetation, and climate (Archibald et al., 2013). Date ranges used for fuel conditioning was determined by identifying a 1-2 week period in which the daily Energy Release Component (ERC) from RAWS weather data was near the 97th percentile "near maximum worst case" conditions. The ERC is a number related to the available energy (BTU) per unit area within the flaming front at the head of a fire and is considered a composite fuel moisture index as it reflects the contribution of all live and dead fuels to potential fire intensity (B. Smith, n.d.). The National Fire Danger Rating System (NFDRS) fuel model G is widely used to display ERC as it contains all of the dead size class fuels and both the herbaceous and woody live fuels (B. Smith, n.d.).

Wind behavior was modeled within IFTDSS using the 'Gridded Winds' option within FlamMap which utilizes a built-in program called WindNinja to compute spatially varying winds across a landscape based on topographic change as well as a drag effect that vegetation has on wind flow (Godwin & Wagenbrenner, 2016). Given the topographic variations within the watershed, gridded wind direction was chosen in order to most accurately model the complex terrain winds within the area of interest.

Burn Severity Classification

For this analysis, we used flame length outputs for each pixel from the fire model run (**Figure 21**) as a surrogate for fire severity. This methodology was common practice in similar studies and is utilized by the Forest Service's Burn Area Emergency Response teams (Buckley et al., 2014; Mary Ellen Miller et al., 2011). For our purposes, we determined that all flames longer than 8 ft. would lead to high severity impacts. We used a crosswalk table (**Table 5**) between flame length and burn severity to estimate post-fire soil burn severity and ground cover.

Table 5. *Crosswalk table for converting FlamMap flame length to burn severity.*

Flame Length	Burn Severity Ranking
0 ft	No Burn
0 – 4 ft	Low
4 – 8 ft	Medium
8+ ft	High

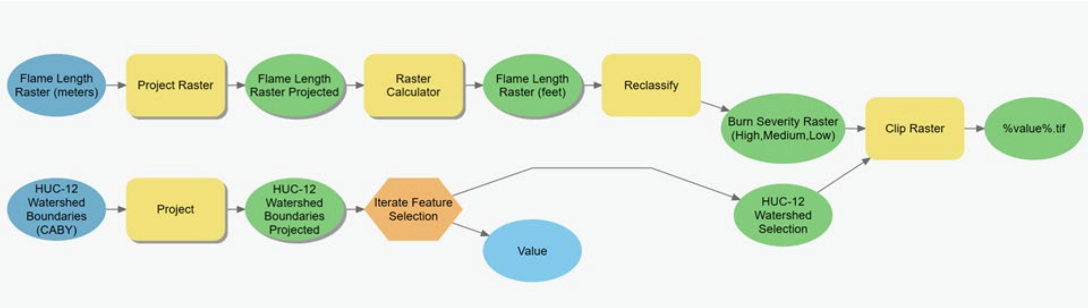

Figure 21. *Model to convert initial flame length raster output to reclassed burn severity raster.*

Flame length raster results for each of the ten modeled “firescapes” were merged and a GIS model was used to project the data into a common coordinate system, convert units from meters to feet, and reclassify flame lengths to low [1], medium]2], and high [3] burn severity ratings (**Figure 21**). The end product was a reclassified burn severity raster for the entire region (**Figure 22**). This burn severity layer was clipped to the boundaries of each HUC-12 within the CABY using ArcGIS iterators to better facilitate erosion modeling at the subwatershed level (**Figure 21**). These respective burn severity layers were used to assign the dominant burn severity type to each hillslope in our erosion model runs in order to simulate changes in soil erodibility and hydraulic conductivity.

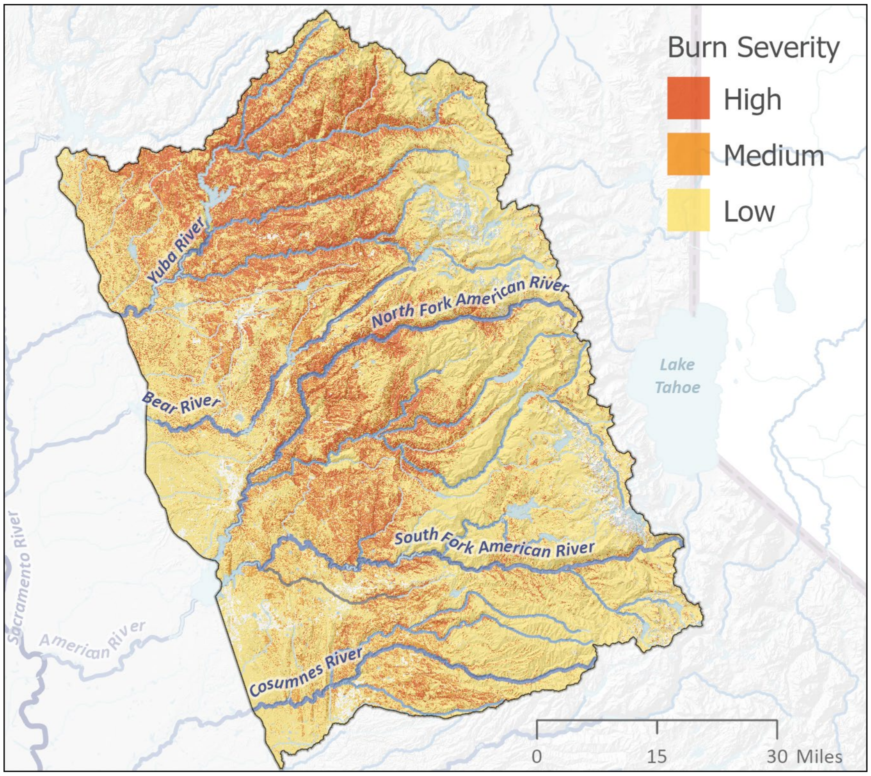

Figure 22*. Burn severity results for the CABY region, reclassified to high, medium, and low severity burns.*

In total, our modeling predicts that approximately 30% of the study area is at risk of experiencing either medium or high burn severity impacts, with the highest concentration of severe fire effects located in the mid-elevation and northern watersheds of the CABY region.

5.9 Erosion Risk

Quantifying the distribution of erosion risk and the potential to reduce hillslope sediment transport into waterways will be a key component in any land management methodology structured around water supply protection. Predicting the effects of fuel reduction treatments on hillslope erosion often requires the use of erosion models in unison with fire models to estimate watershed post-fire sediment yields. The benefit to this modeling approach is the ability to use predictions of post-fire erosion for current conditions along with those after simulated fuel treatments to help prioritize where to place fuel treatments in a watershed. Of the erosion models actively being used in the field today, several were evaluated for use in this project including the Watershed Erosion Prediction Project (WEPP), Revised Universal Soil Loss Equation (RUSLE), the Integrated Valuation of Ecosystem Services and Tradeoff (InVEST) model, and the Soil & Water Assessment Tool (SWAT). By reviewing recent studies that performed equivalent fire-induced erosion modeling in other western watersheds, we decided to utilize the US Forest Service developed WEPP model for our erosion risk analysis (Buckley et al., 2014; Gannon et al., 2019; Sankey et al., 2017).

Model Suitability

WEPP is a physically-based erosion prediction model that integrates information on variables such as elevation, slope, soils, land use, and climate to calculate rill and inter-rill erosion, as well as sediment deposition (Renschler, 2003). In a review of 25 water and sediment modeling tools, the US Forest Service identified WEPP as one of the highest-ranking models for use in forested mountainous environments—scoring high marks in access, ease of use, documentation, defensibility, and overall fit categories (K. Hyde et al., 2006). In addition, WEPP has been shown to more accurately model erosion compared to the RUSLE equations (Larsen & MacDonald, 2007). The WEPP model contains its own process-based hydrology, water balance, plant growth, and soil consolidation models as well as a climate generator, which broadens its range of usefulness (A. K. Tiwari et al., 2000).

WEPP offers several advantages over other models, such as RUSLE, to predict soil erosion. First, WEPP is physically-based, whereas RUSLE is a conceptual model. Conceptual models are based on the observed physical processes that drive watershed responses and rely heavily on empirical data in their application. Because of their reliance on observed data, it is not advised to extrapolate conceptual models to conditions beyond those that were used in their development (Elliot et al., 2010). In contrast, physically-based models such as WEPP use equations to represent the physical processes that describe the system. Input parameters for these models generally are variables that can be measured or derived from measurements of physical or biological processes, such as topography, runoff rates, biomass amounts, and surface cover. Physically-based models are more widely accepted in academia, and have a distinct advantage in that they can be applied to areas other than where the original data that were used for model development were collected (Elliot et al., 2010).

Secondly, WEPP is a “distributed” model as opposed to RUSLE which is a “lumped” watershed model. RUSLE uses a single value to describe soil, vegetation, and climate conditions in the entire watershed, while a “distributed” model like WEPP allows for different values for each grid cell or individual hillslope. This enables interactions between cells within the model, more closely mimicking the “runon-runoff” processes common on disturbed forest hillslopes and yielding more accurate erosion estimates (Elliot et al., 2010). Additionally, this allows users to identify hot spots for sediment sources and select where to focus management. Lastly, use of WEPP does not require any in-depth understanding of the hydrology, hydraulic, and erosion principles embedded within the WEPP model. This allows stakeholders and managers of various backgrounds to run the model with relative ease (M. E. Miller et al., 2016).

WEPP’s sediment modeling accuracy has been assessed in both agricultural and forested settings over the last several decades. As the core formula of the WEPP model has remained the same, these studies have proven useful in supporting our choice of WEPP for erosion modeling in the CABY region. WEPP has been evaluated at both agricultural study sites and in forested settings managed by the US Forest Service. In terms of absolute erosion values generated from WEPP, the accuracy of a predicted runoff or erosion rate is plus or minus 50 percent. At best, any predicted runoff or erosion value by any model will be within only plus or minus 50 percent of the true value. Erosion rates are highly variable, and most models can predict only a single value. Replicated research has shown that observed values vary widely for identical plots, or the same plot from year to year (Dun et al., 2009; Elliot W.J. et al., 1995; Tysdal et al., 1999). Also, spatial variability and variability of soil properties add to the complexity of erosion prediction (Peter R. Robichaud, 1996).

The Disturbed WEPP model interface allows for modeling the differential erosion impacts of disturbances to forested landscapes, such as fire and logging. Disturbed WEPP has been widely applied to model post-fire erosion, and several publications exist evaluating the accuracy of modeled and observed post-fire erosion. A study of post-fire erosion prediction in the Colorado Front Range demonstrated that Disturbed WEPP more accurately predicted sediment yield than RUSLE, although both models provided poor estimations of observed erosion with respective R^2 values of 0.25 and 0.16 (Larsen & MacDonald, 2007). This study also found that WEPP underestimated erosion after high-severity fires by not accounting for the effect of soil transformations on hydraulic conductivity, and the model performed better over hillslope units defined by fire severity than at the smaller plot level, indicating higher accuracy at larger scales. WEPP tends to overestimate sediment yield when erosion is below-average, and underestimat sediment yield when erosion is above-average – a common issue with many erosion models. At the watershed level in the Sierra Nevada, WEPP has demonstrated accurate modeling of sediment distribution with minimal calibration across five diverse tributaries in the Lake Tahoe basin (Brooks et al., 2016). This literature review suggests that Disturbed WEPP is a sound modeling choice for the Forests to Faucets group project.

WEPP Technical Formulae

WEPP simulates both interrill and rill erosion processes and incorporates the processes of evapo-transpiration, plant growth, infiltration, runoff, soil detachment, sediment transport, and sediment deposition to predict runoff and erosion at the hillslope scale (D. Flanagan et al., 1995). WEPP calculates overland flow of sediment from hillslopes to channels, which flow through impoundments (if present) in each subwatershed to the outlet. Soil erosion is represented as soil particle detachment by raindrop impact, sheet flow on inter-rill areas, and transport by flow through rill areas. WEPP is able to model both sediment transport and deposition based on precipitation intensity, slope, roughness, and other parameters. The model incorporates channel hydrology characteristics such as concentrated flow and infiltration into the erosion process as well. Channel computations assume a triangular naturally-eroding cross-section, and channel deposition occurs when sediment load exceeds transport capacity (D. Flanagan et al., 1995).

Within the context of these physically-modeled surfaces, parameters are distributed in downslope strips that may exhibit different soil type and vegetation cover. WEPP then simulates 100 years of stochastic daily climate based off monthly weather parameters from nearby weather stations using an integrated stochastic weather generator. Erosion is quantified off this modeled landscape by averaging sediment delivery across these individual trial runs. Soil detachment is based on slope profile, and sediment deposition in concave or rough vegetated areas is subtracted from total sediment delivery off of individual hillslopes. Baseline soil infiltration and erodibility are calculated based on input soil properties (Bufford, 2018). Importantly, WEPP does not model erosion originating from landslides or debris flows. Empirical models to predict the probability of occurrence and magnitude of debris flow after wildfire exist; however, the empirical parameters inherent in these models may lead to high levels of uncertainties in many watersheds.

Suspended sediment transport is based on the steady-state erosion model from Foster and Meyer (1972) which solves the sediment continuity equation $DG/dx = D_f + D_i$, where x represents downslope distance, G is sediment load, D_i is inter-rill erosion rate, and D_f is rill erosion rate. These two D terms each consist of multiple other parameters such as rainfall intensity, erodibility, runoff rate, sediment delivery ratio, detachment, and sheer stress (A. K. Tiwari et al., 2000; D. Flanagan et al., 1995).

WEPP Erosion Modeling

Erosion modeling was performed for individual HUC-12 subwatersheds within WEPPcloud, an online interface for the WEPP model developed by a joint effort between University of Idaho and the US Forest Service's Rocky Mountain Research Station. WEPPcloud houses a wide range of decision support tools including watershed-scale applications of WEPP. To model post-fire erosion, we used the WEPPcloud-Disturbed interface which provides both hillslope and watershed outlet predictions based on soil burn severity maps uploaded to the interface by users. This tool allows managers to assess the impact of targeted post-fire mitigation efforts on hillslope erosion and watershed response. The ability to apply a process-based spatially distributed hydrology and erosion model online using daily observed climate and soil burn severity maps make this a unique and powerful tool for watershed assessment and management. The key advantage of using the WEPPcloud interface is its facilitation of input data preparation and hydrologic simulations from any computer connected to the internet. This eliminates the need for substantial pre-processing of input data and allows users without advanced GIS experience to model erosion in a watershed of interest. Detailed instructions on using the WEPPcloud-Disturbed interface to model post-fire erosion can be found in Appendix 3.

Required inputs into the WEPP model include climate, topography, soil (including changes to soil erodibility parameters due to fire), and vegetation type (**Figure 23**). WEPPcloud automates the acquisition and processing of climate, soil, management, and topographic inputs for WEPP from publicly available datasets with national coverage including: USGS National Elevation Dataset, the NRCS Soil Survey Geographic Database (SSURGO), USGS National Land Cover Database, and the PRISM database. The WEPPcloud-Disturbed interface backfills soils and managements (landuse) with parameters from the USFS Disturbed database based on the dominant landcover type, soil texture, and predicted/observed burn severity. An advantage of using WEPP-Disturbed in the CABY region is that the interface contains specific data for the greater central Sierra zone that provides better calibration of landuse and soil erosivity parameters. Based on these inputs, WEPP interfaces will calculate stream centerlines and subwatersheds of user-specified sizes. Erosion quantification takes place at the subwatershed level, with different hillslopes within each subwatershed catchment contributing different amounts of erosion, as quantified in total at the stream outlet point of the subwatershed or individually at the hillslope(s) scale.

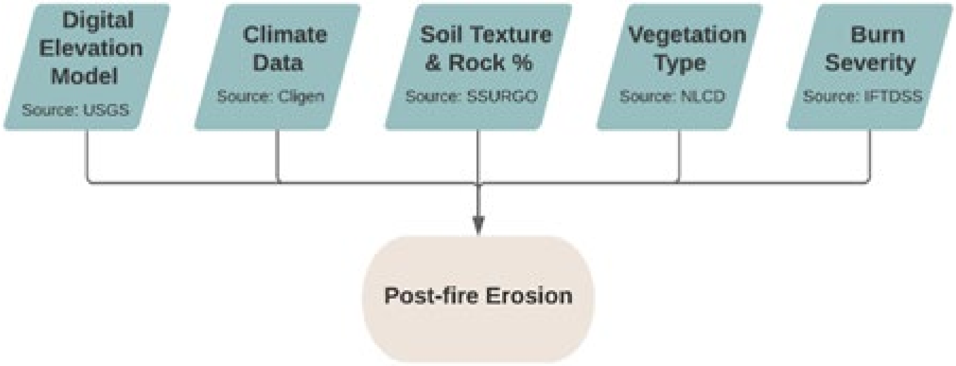

Figure 23. *WEPP model inputs for post-fire erosion modeling.*

Burn severity rasters for each of the eleven subwatersheds selected during the treatment priority analysis were generated by clipping the merged burn severity raster from our fire modeling to the boundary of each individual subwatershed. Each subwatershed was then modeled individually by uploading the respective burn severity raster into the WEPPcloud-Disturbed interface. Two model iterations were completed for each subwatershed, one under a no-treatment scenario and one under a post-treatment scenario in which burn severity was reduced by one class to simulate fuel reductions. WEPPcloud defines watershed boundaries and hillslope polygons using the Topographic Parameterization Landscape Analysis Tool (TOPAZ). Required input parameters for TOPAZ include the critical source area (CSA) and minimum source channel length (MSCL). A 500-foot MSCL and 50-acre CSA were used in this analysis to capture higher resolution erosion results at the HUC-12 watershed level (See Appendix 3).

The single most important factor impacting soil erosion is weather. WEPP uses a stochastic weather generator called CLIGEN (D.C. Flanagan et al., 2001) and a database of 2,400+ US weather stations to generate the climate parameters needed to model run-off and erosion (mean daily precipitation, min/max daily temperatures, dew point, mean daily solar radiation, and mean daily wind speed and direction). These parameters are built using historic monthly values from the nearest weather station site. However, weather is highly variable from year to year and site to site, particularly when these sites are at different elevations. The better the weather can be predicted for a given site, the better the predicted erosion for that site will be. To address this, WEPPCloud allows users tremendous flexibility in climatic input files including spatially explicit PRISM-corrected climate files and future downscaled climate projections. PRISM uses elevations, point sources of climatic data, and other spatial data sets to generate grids of climate data at a resolution of 4 km (Daly & Bryant, 2013). We used the PRISM-Modified climate option within the interface to interpolate precipitation values from a nearby weather station in order to better match the local climate of the modeled watershed. Each model run was set to simulate 50 years of daily stochastic weather.

Model outputs from WEPP include average annual simulated sediment yields from the watershed outlet, each hillslope in the watershed, and each stream channel in the watershed. A return period assessment for sediment yield is also calculated to understand the variability and risk of soil erosion (See Discussion). Our analysis of erosion risk incorporated only average annual hillslope erosion rates to focus on the direct effects of wildfire on soil dynamics and to better facilitate modeling runs on larger watersheds. Due to limitations in both WEPP's online interface and the model's ability to simulate the complex sediment transport dynamics of large rivers, some hillslope areas were unable to be modeled in some subwatersheds. These areas primarily consisted of hillslopes draining directly into mainstem river segments. In order to better account for the cumulative erosion effects of these missing hillslopes an extrapolation process was performed to predict sediment yields for any areas unable to be modeled directly. Where applicable, the total area modeled was divided by the total subwatershed area to calculate the percent of total area modeled with the interface. The total modeled sediment yield was then divided by the percent area modeled to extrapolate the total sediment yield for the entire subwatershed. In order to facilitate comparisons between subwatersheds of varying sizes, the difference between the total pre- and post-treatment sediment yields were then divided again by the total subwatershed area to calculate the annual average sediment reduction per unit area (kg/ha) resulting from fuel treatment. Those watersheds modeled to experience the most avoided sediment loss are higher priority for prescribed fire treatment planning from an erosion risk mitigation perspective.

Erosion Risk Results

Table 6. *Erosion risk results for eleven HUC-12s in the CABY region. Results are reported as avoided sediment loss from fuel treatment.*

HUC-12 Code	HUC-12 Name	Sediment reduction %	Sediment reduction (kg/ha)	Rank	Prioritization Scenario
180201250507	Grizzly Creek-Middle Yuba River	70.5	3,334	1	Equal Weight
180201280107	Indian Creek-North Fork American River	60.2	3,086	2	Mining
180201250402	Slate Creek	63.2	2,522	3	Equal Weight
180201260103	Little Bear Creek-Bear River	65.0	2,332	4	Equal Weight
180201250703	Rock Creek-South Yuba River	66.2	1,895	5	Mining
180201251001	Dobbins Creek-Yuba River	51.8	1,727	6	Equal Weight
180201250704	Shady Creek-South Yuba River	64.5	1,005	7	Equal Weight
180201590101	Rocky Honcut Creek	67.2	943	8	Habitat
180201280502	Canyon Creek	68.3	561	9	Infrastructure
180201250903	Lower Dry Creek	42.2	226	10	Infrastructure
180201290303	Alder Creek	1.1	1	11	Habitat

Since the CABY study area proved too large for full-scale erosion modeling due to data processing and modeling constraints, we prioritized 11 watersheds in the CABY for erosion modeling using the WEPPcloud Disturbed interface. Erosion was modeled in these watersheds for both pre-and post-treatment fire scenarios. The reduction in average annual sediment yield over a 50-year period for each HUC-12 subwatershed is shown in **Table 6 and Figure 24**. The three top subwatersheds for area-adjusted sediment yield reduction (kg/ha) were Grizzly Creek-Middle Yuba River, Indian Creek-North Fork American River, and Slate Creek.

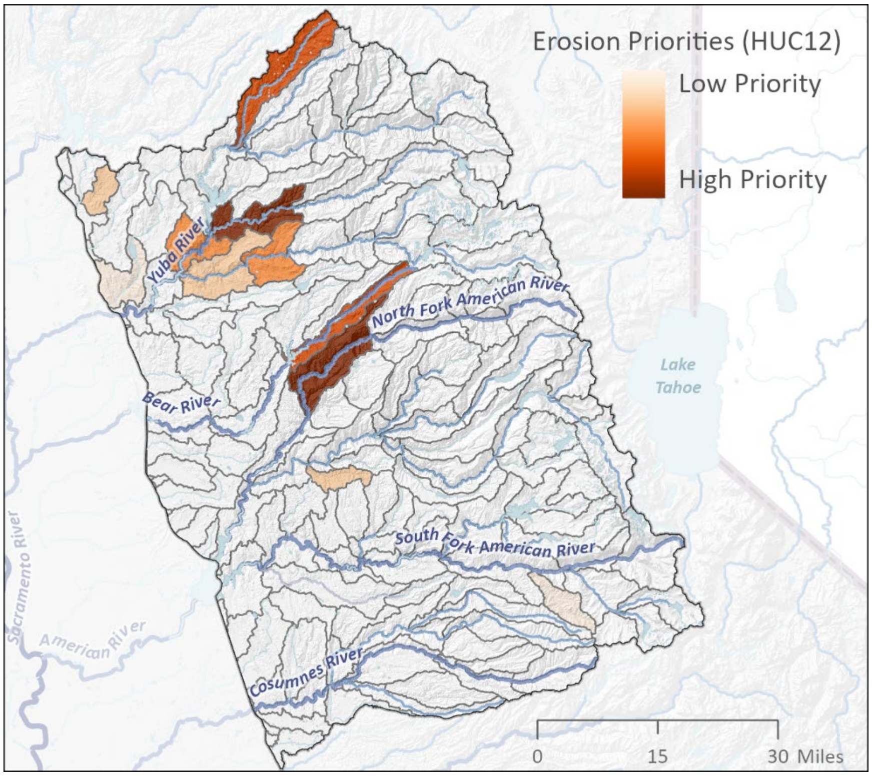

Figure 24. *Erosion priorities depicted at the HUC-12 watershed level. Priorities were determined based upon the avoided sediment loss (kg/ha) of post-fire erosion with treatment. Erosion priorities were only determined for 11 subwatersheds due to modeling and time constraints.*

Erosion Risk Sensitivity Analysis & Discussion

In order to assess the sensitivity of erosion estimates to changes in certain WEPP model inputs—along with how climate change may alter erosion risk in the future—results from a 50-year baseline WEPP run under current climate was compared to 50-year runs under current climate with smaller delineated hillslopes as well as under projected future climate conditions (2010-2060). These comparison runs were modeled using the Slate Creek subwatershed as a test case—a HUC-12 watershed identified as being high-priority for erosion risk analysis in earlier prioritization rankings.

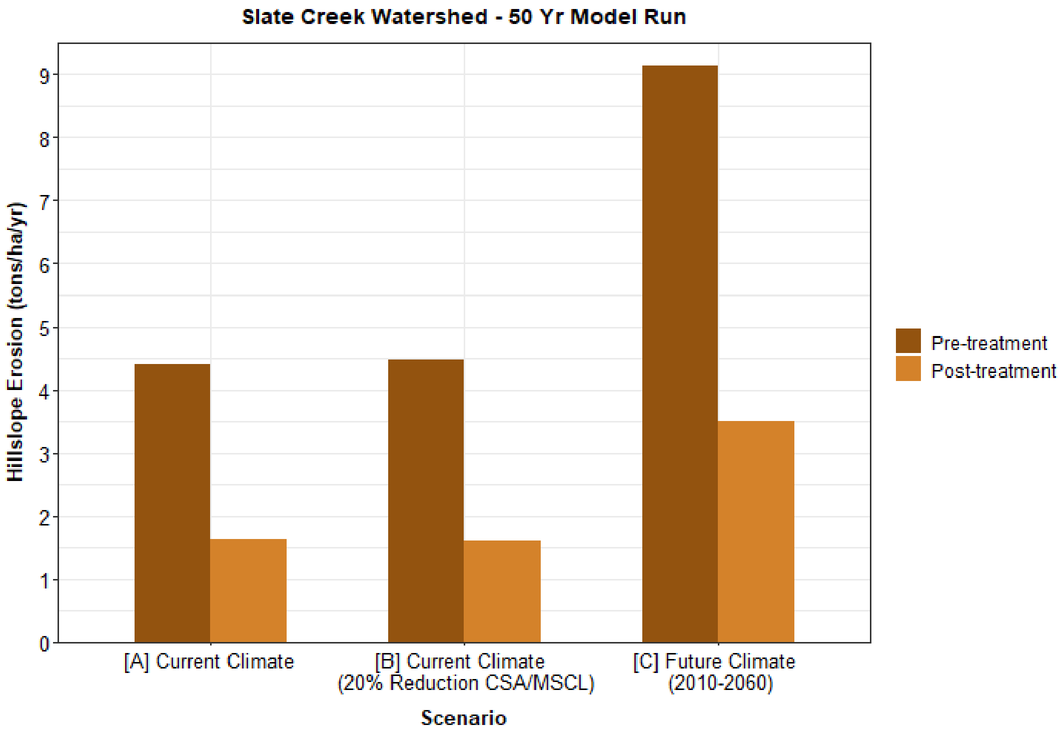

Figure 25. *Erosion values for pre- and post-treatment conditions under different model parameter scenarios. Scenario A: baseline estimate under single-current climate. Scenario B: 20% reduction in critical source area (CSA) and Minimum Source Channel Length (MSCL). Scenario C: estimates under projected future climate conditions (2010-2060) for "business as usual" RCP 8.5 emissions scenario.*

Erosion rate sensitivity to changes in delineated hillslope size:

WEPP uses TOPAZ to parameterize topographic data from DEMs to create hillslope profiles. Adjustments can be made to the detail of the channel network by changing values of Mean Source Channel Length (MSCL) and Critical Source Area (CSA). The MSCL is the shortest length that any channel is allowed to be. The CSA defines the minimum drainage area below which a permanent channel forms (Garbrecht & Martz, 1997). Decreasing these to lower values will increase the density of channels and number of defined hillslopes while decreasing overall hillslope size, potentially capturing finer resolution of erosion processes at the expense of increased processing time. To test the sensitivity of erosion rate estimates to changes in hillslope parameterization we reduced the baseline CSA & MSCL used in our erosion analysis by 20% to 40 acres and 400 ft., respectively. This resulted in an erosion rate increase of 0.07 tons/ha (1.6%) under a pre-treated scenario and a 0.01 tons/ha (0.6%) decrease under a post-treated scenario over the entire subwatershed (**Figure 25**, [B]). While the amount of sediment eroding off hillslopes can increase when incorporating more channels and smaller hillslopes, the difference was negligible at a 20% reduction. Further reductions could not be tested without maxing the WEPP watershed interface's 1,000 hillslope/run limitation. However, we do not expect decreasing CSA & MSCL would alter our final erosion risk recommendations as we would expect to see concomitant negligible increases/decreases in all subwatersheds modeled resulting in a similar ratio of relative erosion risk.

Erosion under future climate projections (2010-2060):

Precipitation extremes will likely intensify under climate change(He et al., 2019). In a study analyzing a collection of climate, fire, and erosion models for 471 large watersheds throughout the western U.S, researchers found that by 2050, the amount of sediment in more than one-third of watersheds could at least double (Sankey et al., 2017). In general, warming is expected across all areas of the CABY region with warming in late century expected to be more significant than warming in mid-century. This warming will cause a rise in the rain-snow transition elevation and lead to a higher ratio of precipitation falling as rain rather than snow (He et al., 2019). Atmospheric river storms contribute largely to the total precipitation in California and serve as a dominant cause of flooding in the state (Dettinger, 2011; He et al., 2019). Particularly, the climatologic peak of atmospheric river landfall is at latitudes that impact major watersheds within the CABY including the Yuba River and American River. Projections show that the frequency of landfalling ARs in California may increase by about 30% by the end of the 21st century (Dettinger, 2011; He et al., 2019).

To estimate the impacts climate change may pose to erosion risk and the efficacy of fuel treatments, we modeled pre- and post-treatment scenarios under a 2010-2060 climate generated from “downscaled” climate projection data from the Coupled Model Intercomparison Project (CMIP5). CMIP5 includes “long term” simulations of twentieth-century climate and projections for the twenty-first century which was relied heavily on in the Intergovernmental Panel on Climate Change’s Fifth Assessment Report (Emori et al., 2016). WEPPcloud interfaces provide the ability to model erosion using interpolated CMIP5 data at a 4-km resolution under Representative Concentration Pathway (RCP) 8.5, commonly referred to as the “business as usual” emissions scenario in climate forecasting. Hillslope erosion for a pre-treatment landscape under a 2010-2060 climate was estimated at 9.1 tons/ha/yr and 3.5 tons/ha/yr for a post-treatment landscape (**Figure 25**, [C]), representing a 108% and 116% increase over current climate erosion estimates, respectively. Under a future climate — despite simulated prescribed burning treatments — post-treatment hillslope erosion was modeled to increase by nearly double (1.62 to 3.5 tons/ha/yr), mirroring the projections for many watersheds throughout the West (Sankey et al., 2017). While there are many compounding uncertainties in using erosion models and climate models in tandem, it can be reasonably inferred that climate change will significantly increase the magnitude of post-fire erosion effects moving forward — solidifying the need to incorporate more hydrocentric considerations into current and future fuel treatment prioritizations.

Return Period Analysis:

Estimating average annual erosion over a modeling period sufficient to capture a range of potential weather scenarios, as determined in this analysis, is one way to evaluate post-fire erosion susceptibility at the watershed and hillslope scale. However, the highest erosional impacts can occur from large storm events in the few years immediately succeeding a wildfire before regrowth of vegetation begins to attenuate erosion potential. Therefore, an alternative method of evaluating erosion risk that may be beneficial to land managers is through a return period analysis, which estimates the probability of a given level of erosion being exceeded each year. When prioritizing treatment areas in terms of fire-induced erosion risk, it may be useful to compare watersheds based on their 2- or 5-year sediment yield recurrence intervals which provides an estimate of erosion thresholds likely to be met or exceeded during the years where erosivity hazard is greatest after a fire. WEPP generates return periods by sorting annual values of sediment yield in a model run by their magnitude. Each year following a disturbance or management treatment, there could be unique vegetative and soil conditions. For each unique vegetative soil conditions, the model simulates 100 possible weather scenarios that could occur and provides probabilistic outputs. For a 50-year run WEPP provides sediment yield thresholds for 2-, 5-, 10-, and 20-year return periods. A five-year value, for example, means that amount of sediment eroded from the watershed will be exceeded about once every five years on the average. Put another way, there is a 20% chance that a value equal to or greater than the five-year value will occur in a given year. Stakeholders can use these estimates to evaluate the likelihood of a particular magnitude erosion event occurring after a wildfire and whether these may exceed management thresholds for highly valued resources or assets downstream. Conducting a return period analysis on pre- and post-treatment conditions can also be helpful in comparing different watershed priorities and determining where erosion risk may be most reduced by fuel treatments in probabilistic terms.

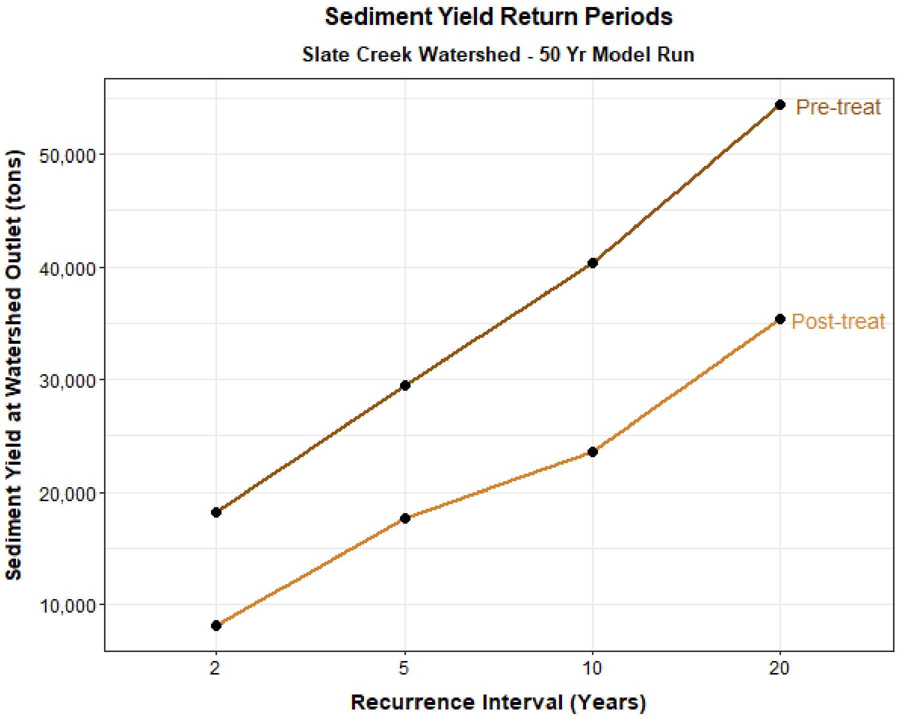

Figure 26. *Estimated sediment yield return periods for the Slate Creek watershed.*

Using the Slate Creek subwatershed as a test case (**Figure 26**), we see there is a 50% chance that the annual sediment yield for the entire subwatershed will exceed 18,141 tons and a 20% chance of exceeding 29,478 tons in a given year. After simulating fuels reductions, the 2- and 5-year recurrence intervals are 8,163 and 17,687 tons, respectively. This results in a 45% reduction in the 2-year return interval and a 60% reduction in the 5-year return interval. This analysis did not conduct a full return period analysis assessment for priority watersheds as it was determined that average annual erosion estimates provided adequate indicators in making comparisons of relative erosion potential between watersheds. Additionally, our erosion analysis focused on hillslope erosion only where the return period values within the WEPPcloud system also include modeled channel erosion in its calculations. However, a return period analysis is another tool in the hydrocentric prioritization of fuel treatment locations that can be utilized by planners through the WEPP model if desired.

Sediment Size Class & Type Analysis:

In some cases, planners may wish to estimate the distribution of eroded sediment type and size that may be mitigated by fuel treatments in different locations. Target sediment types and size will depend on management goals and the water resource of concern. Some stakeholders may focus on sand as the size of concern because it is readily deposited in stream systems, filling in spawning areas around and under gravel. Others may be more concerned with silt content as it is more of a problem in decreasing the clarity of the water, as well as reducing the quality of the aquatic ecosystem on the channel bottom.

WEPP predicts the size distribution of eroded sediment and provides the distribution of sediment in each of the size classes in the soil, and in the eroded sediment. As mitigation goals for particular sediment types are highly dependent on specific management objectives in a given area, our results did not factor in this type of analysis. However, if desired stakeholders can utilize the online interface to the WEPP model to perform this analysis for a subwatershed of interest.

Future Directions in Erosion Modeling

While existing WEPP tools are easy to use and suitable for land managers to quickly understand the effects of fire and other disturbances on erosion over small areas, there remains a need for products that automate WEPP over complete watersheds without requiring labor-intensive and error-prone manual modeling approaches. For example, open-source R and Python packages exist to run the SWAT model, but our group could only identify one R package for running WEPP (WEPPR) that is still in development, as well as a Python package that was not well-documented (wepppy). Unlike WEPP, SWAT is extremely sensitive to several dimensionless input parameters and requires an involved calibration process that was beyond the scope of this project. While the WEPP formula's hillslope length limitations will continue to be an obstacle in applying this model in mountainous areas, the academic community would greatly benefit from a well-documented open-source package to run the WEPP formulae in a coding environment, enabling wide applicability of the model over large scales using general programming approaches.

5.10 Treatment Selection

Avoided sediment loss was incorporated with habitat, infrastructure, local water quality, and equity priorities along with burn probability in order to identify the HUC-12 watersheds recommended for treatment. Each of the 11 watersheds identified as high value in the initial prioritization received a score equivalent to the weighted sum of the six components. The weight given to each component was determined through internal team meetings and in conversation with American Rivers. Future users of this methodology could choose to assign different weights according to their priorities. The three watersheds with the highest score in this prioritization were recommended for treatment.

Fire severity was included as a component in the final prioritization at the request of American Rivers. To prioritize fire severity, we determined the percentage of each watershed that was predicted to burn at high severity under current conditions and rescaled these values to yield a fire severity score ranging from 1 to 5 (**Figure 27**).

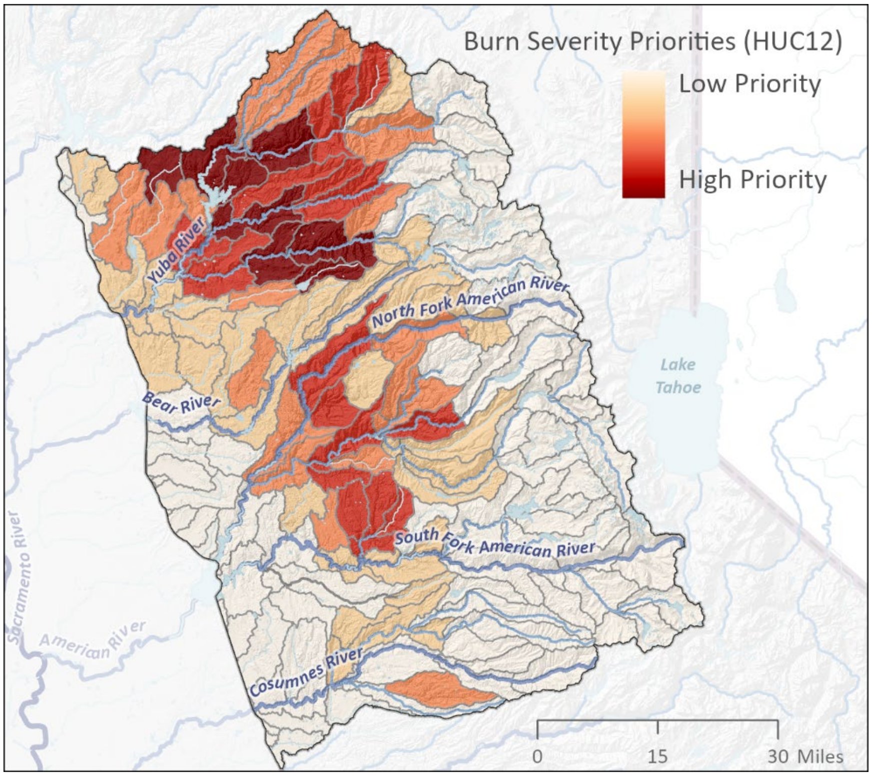

Figure 27. Burn severity priorities by HUC-12 watershed across the CABY region.

We conducted the final prioritization with three different weightings to explore how the treatment recommendations would vary under different scenarios. The three scenarios were 1) equal weighting (without fire severity), 2) American Rivers weighting (with fire severity), 3) American Rivers adjusted weighting (without fire severity) (**Table 7**). The American Rivers weighting scenario was developed by staff of the Headwaters division after conversations with our tream. The weights in the American Rivers adjusted scenario were calculated by removing fire severity and rescaling the weights of other components proportionally. This scenario was created due to concern that including fire severity in the prioritization "double counted" fire severity since it is already a key component of avoided sediment loss. In addition, we felt that including fire severity as a primary component shifted the focus of the prioritization away from water resources, as our research indicated that post-fire sediment yield is the primary pathway by which high severity fire impacts water resources. The prioritization results from all three scenarios are included as options for American Rivers and demonstrate how the methodology can be adapted to different priorities.

***Table 7**. Weights assigned to each prioritization component in three different weighting scenarios: Equal Weights, American Rivers, and American Rivers adjusted. Component weights for each scenario add up to 100.*

Prioritization Component	Equal Weight Scenario	American Rivers Scenario	American Rivers Adjusted Scenario
Fire Severity	0	40	0
Erosion Risk	16.66	20	33.33
Infrastructure	16.67	15	25
Equity	16.67	10	16.67
Habitat	16.66	8	13.33
Local Water Quality	16.67	4	6.67
Burn Probability	16.67	3	5

Results of the treatment selection prioritization are shown in **Figure 28** and **Table 7** with both ranks and scores. While there is some variation in how watersheds are ranked in each scenario, two watersheds, Slate Creek and Little Bear Creek, are ranked in the top three in all three weighting scenarios. This suggests that our model is moderately robust to variation in component weights. Final treatment recommendations for the CABY region were based on the results of the prioritization using the American Rivers adjusted weights since this scenario best captured the interests of our client and maintained the focus on water resources.

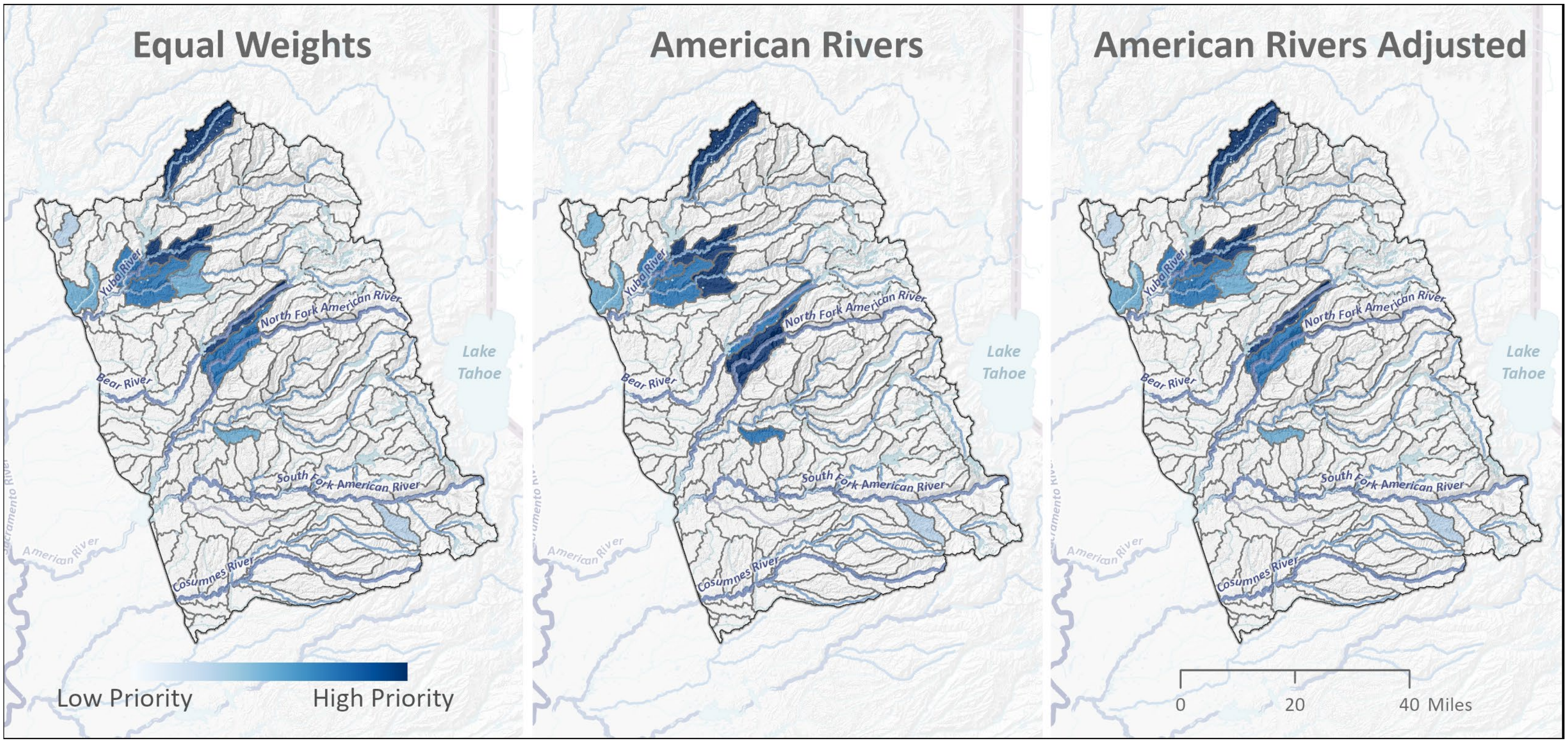

***Figure 28.** Output of treatment selection prioritization for three different weighting scenarios.*

Table 7. *Watersheds ranked by treatment selection prioritization. Watershed rank is shown for the three treatment selection scenarios. Treatment selection score is indicated in parentheses. Scores are out of a possible 500. The top three ranking watersheds are highlighted in blue for each scenario.*

HUC-12	Equal Weight Scenario	American Rivers Scenario	American Rivers Adjusted Scenario
Alder Creek	11 (118)	11 (77)	11 (104)
Canyon Creek	8 (155)	8 (254)	7 (190)
Dobbins Creek – Yuba River	6 (211)	5 (275)	5 (249)
Grizzly Creek – Middle Yuba River	3 (247)	1 (374)	3 (290)
Indian Creek – North Fork American River	4 (228)	4 (277)	4 (256)
Little Bear Creek – Bear River	2 (264)	7 (256)	1 (309)
Lower Dry Creek	9 (141)	10 (151)	9 (169)
Rock Creek-South Yuba River	7 (196)	3 (277)	8 (179)
Rocky Honcut Creek	10 (128)	9 (158)	10 (141)
Shady Creek-South Yuba River	5 (213)	6 (267)	6 (213)
Slate Creek	1 (324)	2 (283)	2 (297)

5.11 Limitations

There are a number of limitations and sources of uncertainty in our fuel treatment prioritization that are due to the limited scope of the project, along with the availability of data and inherent model bias. The main limitations of this analysis are detailed below, with specific data constraints identified in the tool handbook.

- **Edge effects of treatment:** Our methodology does not account for edge effects of prescribed fire to reduce fire severity beyond the treatment area. Studies have shown that prescribed fire reduces the wildfire risk in areas adjacent to the treatment footprint (Buckley et al., 2014). However, because we were unable to model fire behavior following treatment, our methodology assumes that treatment will reduce fire severity within the treatment area only. Therefore, it is possible that treatment will result in even greater benefits than our model predicts.
- **Downstream sediment delivery:** Our methodology also does not capture the downstream movement of sediment between watersheds. While the prevalence of dams in the CABY region limits the movement of sediment through the watershed, it is likely that post-fire erosion in the upstream subwatersheds could result in sediment delivery to the downstream subwatersheds. Aggregation of sediment yield at the HUC-12 level captures local movement of sediment, but not movement between subwatersheds. Transportation of sediment via higher order streams (e.g., Yuba, American, Bear, Cosumnes) is not captured using the simplistic in-stream sediment transport algorithms of WEPP, which is unable to simulate the complex sediment transport

dynamics of large rivers. Users of this method should holistically evaluate the potential downstream impacts of post-fire erosion in their target watershed.

- **Water quality impacts of prescribed fire:** This methodology does not account for any water quality impacts that may result from treatment implementation. In the Sierra Nevada, prescribed fire has been shown to have minimal, short-term impacts on water quality (R.S. Arkle & Pilliod, 2010; Bêche et al., 2005; Scott L. Stephens et al., 2004). However, it is possible that prescribed fire impacts may be increased in some areas due to location specific factors. In addition, it may be necessary to pre-treat an area prior to conducting a prescribed burn, and pre-treatment methods may have their own water quality impacts. For example, mechanical thinning is a common pre-treatment technique that can cause significant erosion and sediment delivery to streams (Evans et al., 2011; Reid, 2010). These impacts have not been modeled or otherwise taken into account in our prioritization as the impacts of treatment are assumed to be minimal compared to the water quality impacts of wildfire.
- **Debris flow potential:** While uncommon, post-fire debris flows can have significant negative effects on stream ecosystems and water quality. These impacts are often more severe and longer-lasting than those associated with normal post-fire erosion (K. D. Hyde et al., 2017). While the conditions and sequence of events leading to debris flows is understood, predicting if and where a debris flow will occur remains highly uncertain. Additionally, the probability of a post-fire debris flow occurring is low as most burned watersheds will produce sediment laden flows in response to heavy precipitation (Buckley et al., 2014). Therefore, we chose not to account for the potential impacts of debris flows in our methodology. Empirical models developed by the United States Geological Survey (USGS) to assess post-fire debris flow threats in the intermountain west are available. However, we want to emphasize caution when using these models as there are some empirical parameters in the model that might not be appropriate for some watersheds. We recommend that future users of this method investigate debris flow potential in high priority watersheds as the science of predicting post-fire debris flows evolves.
- **Data & model inaccuracies:** Each subcomponent of our analysis has the potential to introduce data and modeling inaccuracies. The fire and erosion models in particular are trying to represent physical processes and are not able to account for all factors that influence these processes. We have used the best available models at this time, but it is important to acknowledge the potential inaccuracies in this approach. In addition, model bias and uncertainty around model parameters could introduce inaccuracies into our analysis. We made a deliberate choice to use only publicly available datasets that covered the entirety of the Sierra Nevada so that this methodology could be applied in other regions. However, this also meant that we may have not been using the most accurate or up-to-date data sets. We have designed the tool so that it is easy to update the data inputs if the models and datasets improve, or if there is higher quality local data. Local knowledge will be essential when siting fuel treatments to account for the potential errors in the source datasets.
- **Climate change:** Due to time and modeling constraints, we were unable to incorporate climate change into our fire and erosion models. These models both use historical weather patterns to predict current risk, which is likely underestimating actual risk due to changing climate conditions. As we look to the future, local predictions show that wildfire frequency, extent, and severity will likely increase, as will the risk of wildfire-induced erosion (Buckley et al., 2014). Due

to the current and ongoing climatic changes, it is likely that our model underpredicts fire probability, fire severity, and erosion potential.

In addition, each component of the prioritization is based on assumptions and has its own limitations. These are addressed in the tool user manual.

6. Recommendations

6.1 Treatment Recommendations

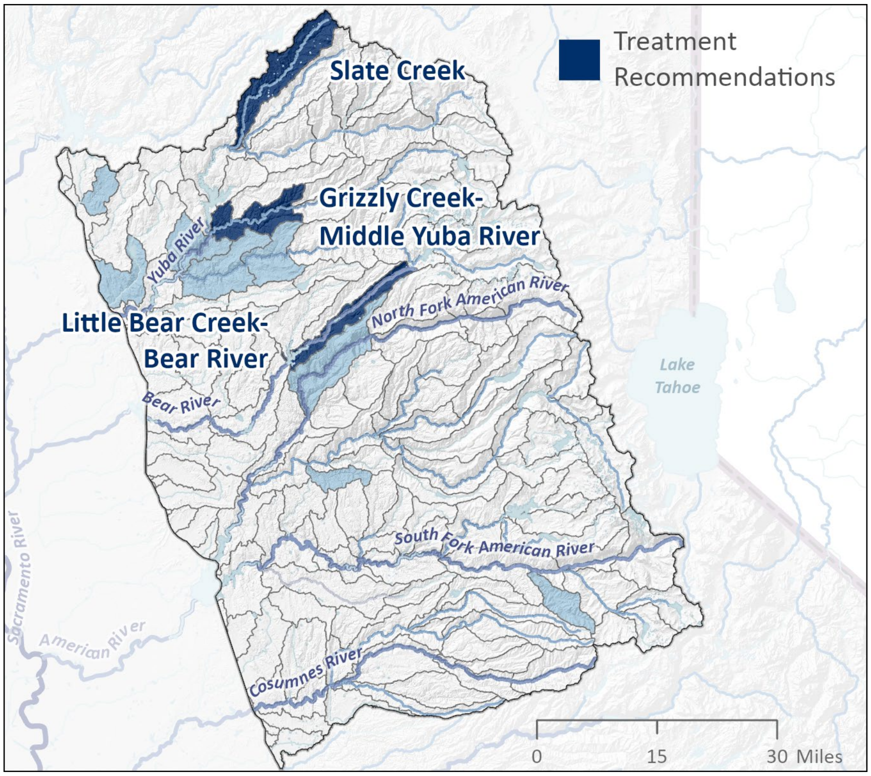

Figure 29. *Subwatersheds that are recommended for treatment by the Forests to Faucets team.*

Under the American Rivers adjusted weight scenario, we recommend prioritizing fuel treatments in three subwatersheds of the CABY: Grizzly Creek – Middle Yuba River, Little Bear Creek – Bear River, and Slate Creek (**Figure 29**). These three watersheds represent areas where prescribed fire has the highest potential to avoid the negative water quality impacts of high severity wildfire while also prioritizing low-income communities. See Appendix 4 for detailed maps of these watersheds.

Little Bear Creek – Bear River is part of the Bear River watershed. Approximately 57% of the watershed is feasible for treatment using prescribed fire. While a large portion of the watershed is privately owned, 18% (4,009 acres) is owned by the federal government (USFS, BLM). Approximately 22% of the watershed is at high risk of high severity wildfires. Water resources at risk of high severity wildfire in the watershed include three sensitive species (riffle sculpin, western pond turtle, Sierra Nevada yellow-legged frog) and three reservoirs (Dutch Flat and Rollins owned by Nevada Irrigation District, and New Drum owned by PG&E). Implementing prescribed fire in the watershed would lead to an estimated avoided sediment loss of 2,332 kg/ha (65% reduction).

Grizzly Creek – Middle Yuba River is a 25,770-acre watershed within the greater Yuba River watershed. There are a number of land owners within the watershed; significant acreage is owned by private landowners (62.0%), the US Forest Service (35.1%), BLM (2.1%), California State Parks (0.4%), and local governments (0.3%). 61% of the watershed is at risk of high severity wildfire. If treated, several vulnerable water resources at risk of high severity fire would be more protected including the Hour House reservoir owned by Yuba County Water Agency and hardhead fish, western pond turtles, and Sierra Nevada yellow-legged frogs. Prescribed fire is feasible in approximately 65% of the watershed. Prescribed fire could lead to a 70.5% reduction in post-fire erosion within the watershed for an average avoided sediment loss of 3,334 kg/ha.

Slate Creek lies on the northern most boundary of the CABY region and is part of the Yuba River watershed. Over 95% of the watershed is feasible for treatment and the majority of the watershed is owned by the US Forest Service (76%). Vulnerable water resources that would be at risk of a high severity fire include western pond turtles and Sierra Nevada yellow-legged frogs, along with the Slate Creek Reservoir owned by South Feather Water & Power Agency. Approximately 32% of the watershed is at risk of high severity wildfire. Prescribed fire in this watershed would lead to an estimated avoided sediment loss of 2,522 kg/ha (63% reduction).

To treat these watersheds, we recommend that American Rivers pursue grant funding and begin site-specific planning for prescribed fire. Our high-level prioritization has not captured many of the site-specific feasibility constraints of prescribed fire, so we recommend that American Rivers consider landowner interest, air quality regulations, staff capacity and all of the other factors that influence fuel treatments within the region.

In addition, we recommend taking the following considerations into account when investigating treatment opportunities in the Sierra Nevada:

- **Existing fuel treatment efforts:** Our stakeholder interviews and literature review indicated that there are several large fuel treatment efforts currently underway in the CABY region. Examples include the North Yuba Forest Partnership, the Caples Ecological Restoration Project, and the French Meadows Project. We recommend that American Rivers direct their efforts toward areas that are not actively being treated as part of these projects. Furthermore, we recommend that American Rivers connect with existing fuel treatment partnerships to collaboratively plan future burn projects.
- **Treating in riparian zones:** As noted earlier in this report, riparian zones have historically been excluded from fuel treatment due to legal constraints designed to protect water quality and sensitive riparian habitat. However, this has led to denser riparian vegetation than would have been present historically, and, in recent years, stream corridors have been shown to act as channels for wind driven fire, with increased fire severity under certain conditions (North, 2012). Prescribed fire is an ideal strategy to address this problem since it has been shown to have negligible impacts on stream water quality, even when fire is used in the riparian zone. Given this, we recommend that riparian areas be included in the treatment plan to reduce their risk of becoming conduits for fire spread and to increase riparian health. In addition, we recommend

continued monitoring of science on this topic since it is likely that research will be increasing on this relatively unstudied topic.

- **Cultural burning:** Before the arrival of European settlers, indigenous people engaged in cultural burning in the Sierra Nevada. We recommend that American Rivers acknowledge the cultural origins of prescribed burning and take steps to include tribal leadership in their project planning. To the extent possible, indigenous people should be included in burn implementation as well as the planning process. We recommend that American Rivers connect with existing indigenous fuel treatment groups such as the Indigenous Peoples Burning Network (IPBN) before initiating any future prescribed fire projects.
- **Future target areas:** Pace and scale of fuel treatment varies widely throughout the Sierra Nevada. We recommend that American Rivers focus its future efforts in those regions where fuel treatment rates have been well below what is needed to reduce the spread of high severity fires. Specifically, we recommend focusing on the headwaters of the Stanislaus, Tuolumne, and Merced rivers as well as the headwaters of the Kern and Kaweah Rivers, all of which had treatment rates between 2 and 14 percent in the last decade (McCann & Xiong, 2021).
- **Best available science:** Our model is based on peer-reviewed research published through 2020. As research on wildfire, fuel treatment, and post-fire erosion evolves, we recommend that American Rivers keep abreast of new findings and periodically evaluate the utility of this tool in light of new research. We recommend that American Rivers base its management decisions on the most up to date science available.

Riparian Fuel Treatment Limitations

Legislation as it stands does not create enabling conditions for fuels reduction in riparian areas. Foresters and private landowners face challenges in justifying activities in riparian areas and short-term disturbances to local flora, fauna, and water quality. However, legislation has the potential to support fuels reduction practices if their aim is long-term water quality protection.

Many foresters decide to block off riparian areas and critical habitat, and exclude them from Timber Harvest Plans (Graydon et al., 2020). Treating in riparian areas is possible and legal if done properly. It does take experience and skill to navigate the riparian areas taking into consideration local specifications (slope, soils, water course characteristics etc.) while ensuring fire edges up to the riparian area but does not burn within 100 feet of the water's surface. By not treating critical habitat and riparian areas fuels build up and put those areas at risk of high severity wildfires (Hunt et al., 2020; Malcom North et al., 2020). However, riparian areas can also act as buffer due to foliar moisture content (Cooper, 2020). This can depend on elevation and aspect and species composition (Cooper, 2020).

6.2 Model Recommendations

Across the state, there has been increased focus and funding for wildfire related research and data development. In the course of our project, we have encountered or heard about several in-development datasets that could improve the accuracy of our analysis. We have designed the model so that these inputs could be easily integrated when they become available in the future. Some likely inputs are:

- **California Forest Observatory:** Released in September 2020, this dataset uses artificial intelligence, satellite imagery, and LiDAR to provide detailed up-to-date information on vegetation and fuel conditions. Given the recent release date, we were unable to incorporate this into our analysis, however, it could be used in the future to replace LANDFIRE data in the fire severity modeling and feasibility analysis. The California Forest Observatory data is an improvement on LANDFIRE for both resolution and frequency of updates - its resolution is 3 meters as opposed to LANDFIRE's 30 meters, and is updated at least yearly while LANDFIRE hasn't been fully updated since 2016.
- **Fuel Treatment Data:** One limitation of the feasibility analysis was limited access to fuel treatment areas. At the time of analysis, we were only able to include treatments on US Forest Service lands (approximately 55% of the watershed). In the future, this limitation could be resolved by incorporating data from the California Vegetation Treatment Program (just started in 2019), CalFire Timber Harvest Plan records, and CalFire prescribed fire event reporter. Many of these layers were unfortunately not identified until late in the project and so were unable to be incorporated, but have been used to calculate treatment statistics for the region (McCann & Xiong, 2021). In the future, it would benefit this type of analysis if one dataset could be developed that captured all treatment efforts across the state, regardless of land ownership.
- **Fire Severity Modeling:** Fire behavior is complex and varies greatly depending on environmental factors. Modelling fire behavior is challenging and requires parametrization in order to get the most accurate results. We modeled fire severity as accurately as we could, but we know that experts have modeled fire severity for the region that is likely more accurate than our results. We attempted to obtain this fire severity data in the course of our project, but were obstructed by trying to obtain fire data in the fall of one of California's worst fire years. In the course of our interviews, we discovered that fire modeling has been completed by Pyrologix across the Sierra Nevada for the US Forest Service, and, more recently, across most of the CABY region as part of the Tahoe-Central Sierra Initiative (E. Smith, 2020; Striplen, 2020). If this data could be acquired, it could improve the fire probability and fire severity portions of the analysis. In addition, the results of the avoided sediment loss analysis would be improved if fire severity modeling could be completed once a treatment location was identified, as opposed to assuming a one burn severity class reduction.
- **Water Equity Data:** Water accessibility and water affordability data created by the Office of Environmental Health Hazard Assessment (OEHHA) was released in early 2021. Currently the equity prioritization is focused on communities that would be vulnerable to wildfire response and that lack the resources to advocate for treatment funding. This data could be used to expand the equity analysis to communities where clean water supply is already at risk and where wildfire impacts would be particularly disastrous.

In addition, we ran into several portions of the analysis where there was insufficient data or modeling capabilities where we would recommend increased research and development. Specifically, we would recommend that fish range data be refined and that modeling erosion across large areas with WEPP be improved. The fish range data that was publicly accessible was limited to HUC-12 level ranges. Preferably, this would be improved to show fish ranges at a stream-level, although this might not be feasible due to sensitive species protections. Under ideal conditions, we would have preferred to model avoided sediment loss across the entirety of the CABY and include the results as a key part of the prioritization. However, this was unfeasible due to the scale of the analysis and deprecated batch processing software. We recommend that tools be developed to model erosion across larger scales through batch processing in R, GIS programs, or in the online interface to improve future similar analyses.

7. Conclusions

Every year, fires are burning more area at a higher severity than has ever been seen before, threatening California’s already delicate water systems. After a high-severity fire, the landscape is more vulnerable to erosion which can threaten drinking water supply, damage critical water infrastructure, and harm aquatic habitat for sensitive species. Fuel treatments, including prescribed fire, have been shown to reduce fire severity and lessen the negative post-fire water quality impacts of high severity fire. However, our literature review and stakeholder engagement indicated that vulnerable water resources are not currently a component of fuel treatment prioritizations.

We developed a decision support tool to prioritize locations for prescribed fire that is focused on the water quality impacts of high severity wildfire. Our tool focuses on vulnerable habitat, water infrastructure, and local water quality issues, while incorporating burn probability, equity in treatment location, and avoided sediment loss of prescribed fire. While the CABY region has been the focus of this paper, the tool is designed to be easily transferred to other regions and can be customized to incorporate each user's individual priorities.

Our tool will help land managers include water quality in locating prescribed fire to minimize the damages to our critical water supply and sensitive riparian habitats, preserving some of our most vital systems from further damage as climate change increases the risk of high-severity wildfire.

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9. Appendices:

Appendix 1: Data Descriptions

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
General Datasets:						
CABY_Boundary.shp	DWR, modified for CABY IRWM	CABY IRWM Boundary.	2017/07/31	Sierra Water Workgroup	2020/10/02	
HUC-12_Boundaries.shp	USGS/ US DOI, modified by CABY IRWM	HUC-12 watershed boundaries.	2018/08/24	Sierra Water Workgroup	2020/10/02	Metadata
Feasibility Analysis Datasets:						
FireHist_CABY.shp	CAL FIRE, USDA Forest Service Region 5, USDI Bureau of Land Management and National Park Service, and other agencies	Fire perimeters for California (1878-2019).	May 2020	FRAP	2020/10/07	Metadata
WUI.shp	University of Wisconsin-Madison Silvis Lab	Wildland urban interface (WUI) for all areas within the coterminous United States (2010).	2017	Silvis Lab	10/16/2020	Metadata
Power_Lines.shp	California Energy Commission	Electric transmission lines and some sub-transmission lines throughout California. Transmission line voltages range from 110 kV to 765 kV. Sub-transmission line voltages range from 33 kV to 100 kV.	5/11/2020	BIOS (Biogeographic Information and Observation System) Viewer	10/20/2020	Metadata
Inventoried_Roadless_USFS.shp	US Forest Service	Polygons represent the national Inventoried Roadless Areas (IRAs) designated by the 2001 Roadless Area Conservation Rule.	10/16/2018	USFS ArcGIS Hub	10/16/2020	Metadata
USFS_Fuel_Treatment_Reduction.shp	US Forest Service	Hazardous fuel treatment polygons that occur on all US Forest Service lands. Treatments include any vegetation manipulation and/or removal/modification of wildland fuels to reduce the likelihood of ignition, to reduce potential fire intensity and spread rates, to lessen potential damage and resistance to control, or to limit the spread and proliferation of invasive species and diseases.	09/28/2020	USFS ArcGIS Hub	10/14/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Fire Severity Modeling Datasets:						
Landfire Landscape (.LCP) file(s)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S Forest Service and U.S. Department of the Interior)	LANDFIRE Landscape (.LCP) files are a multi-band raster format used by wildland fire behavior and fire effect simulation models such as FARSITE and FlamMap. The bands of an .LCP file store data that describe terrain, tree canopy, and surface fuel. LCP files include the following individual geospatial layers needed to run wildfire models: Fuel Model, Canopy Cover, Forest Canopy Height, Canopy Base Height, Canopy Bulk Density, Aspect, Slope, Elevation.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata
40 Scott and Burgan Fire Behavior Fuel Model [FBFM40] (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	40 Scott and Burgan Fire Behavior Fuel Model (FBFM40) is a raster that represents distinct distributions of fuel loading found among surface fuel components (live and dead), size classes, and fuel types. This set contains more fuel models in every fuel type (grass, shrub, timber, slash) than Anderson's set of 13. The number of fuel models representing relatively high dead fuel moisture content increased, and fuel models with an herbaceous component are now dynamic, meaning that loads shift between live and dead (to simulate curing of the herbaceous component) rather than remaining constant.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Fire Severity Modeling Datasets:						
Forest Canopy Cover [CC] (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	LANDFIRE's (LF) Forest Canopy Cover (CC) describes the percent cover of the tree canopy in a stand. Specifically, canopy cover describes the vertical projection of the tree canopy onto an imaginary horizontal surface representing the ground's surface. Used in the calculation of Canopy Bulk Density and Canopy Base Height, CC supplies information to fire behavior models to determine the probability of crown fire initiation, provide input in the spotting model, calculate wind reductions, and calculate fuel moisture conditioning. These products are provided for forested areas only.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata
Forest Canopy Height [CH] (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	LANDFIRE's (LF) Forest Canopy Height (CH) describes the average height of the top of the vegetated canopy. These products are provided for forested areas only. Used in the calculation of Canopy Bulk Density and Canopy Base Height, CH supplies information to fire behavior models to provide input in the spotting model and calculate wind reductions. These products are provided for forested areas only.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Fire Severity Modeling Datasets:						
Canopy Base Height [CBH] (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	LANDFIRE's (LF) Forest Canopy Base Height (CBH) describes the average height from the ground to a forest stand's canopy bottom. Specifically, it is the lowest height in a stand at which there is enough forest canopy fuel to propagate fire vertically into the canopy. CBH provides information for fire behavior models to determine areas in which a surface fire is likely to transition to a crown fire. These products are provided for forested areas only.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata
Canopy Bulk Density [CBD] (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	LANDFIRE's (LF) Forest Canopy Bulk Density (CBD) describes the density of available canopy fuel in a stand. It is defined as the mass of available canopy fuel per canopy volume unit. CBD supplies information for fire behavior models, such as FARSITE, to determine the initiation and spread characteristics of crown fires across landscapes. These products are provided for forested areas only.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Fire Severity Modeling Datasets:						
Aspect (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	Aspect represents the azimuth of the sloped surfaces across a landscape.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata
Slope (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	Slope represents the change of elevation over a specific area.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Fire Severity Modeling Datasets:						
Elevation (for AOI)	LANDFIRE (LF), Landscape Fire and Resource Management Planning Tools (U.S. Forest Service and U.S. Department of the Interior)	Elevation represents land height, in meters, above mean sea level.	LF Remap 2016 products reflect circa 2016 ground conditions. However, LF Remap fuels products in disturbed areas have been revised to expected 2019 or 2020 vegetation conditions, making the fuels products 2019 or 2020 capable.	IFTDSS	10/2020	Metadata
HUC-8_Boundaries.shp	USGS/ US DOI, modified by CABY IRWM	HUC-8 watershed boundaries (used to divide CABY into ten smaller "firescapes" for fire modeling purposes.	2018/08/24	Sierra Water Workgroup	10/2020	Metadata
Pyrome_USA.shp	Short et al., 2016, modified by IFTDSS & the Wiland Fire Management RD&A Program	Fire pyromes of the United States.	2018/09/17	Wildland Fire Management RD&A Program IFTDSS	10/2020	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Erosion Risk Prioritization Datasets:						
WEPPcloud-Disturbed Interface	University of Idaho, Forest Service Rocky Mountain Research Station, USDA ARS, Swansea University, and Michigan Technological University	WEPPcloud is an online interface for the WEPP model that facilitates input data preparation and hydrologic simulations for pre- and post-fire erosion modeling. WEPPcloud automatically generates required inputs for the WEPP model based on a user specified area of interest and burn severity raster file. This includes: 30m DEMs, land cover data (National Land Cover Database), soils data (SSURGO/STATSGO), and climate data (NSERL CLIGEN/PRISM/CMIP5). The WEPPcloud-Disturbed interface backfills soils and managements with parameters from the USFS Disturbed database based on landcover type and soil texture.	2018 - Current	WEPPcloud	2021/01	Metadata
Habitat Prioritization Datasets:						
CARedLgdFrg.tif	CDFW	Predicted habitat suitability for the California red-legged frog.	2016/09/14	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/07	Metadata
Critical_Aquatic_Refuges.shp	USFS, modified by CABY IRWM	Critical Aquatic Refuges located in the CABY IRWM region.	2017/08/24	CABY IRWM	2020/10/07	Metadata
Critical_Habitat_poly.shp	USFWS, modified by SWWG	Specific geographic areas (polygon) that contain features essential for the conservation of a threatened or endangered species (Sierra Nevada yellow-legged frog & California red-legged frog) and that may require special management and protection.	2017/08/24	CABY IRWM	2020/10/07	Metadata
Disappearing_Rivers.shp	Center for American Progress & Conservation Science Partners	Percent human alteration of rivers and streams in the Western United States. Captures alteration to both stream flow and floodplains.	2017/12/04	Data Basin	2020/12/15	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Habitat Prioritization Datasets:						
FoothillYlwLgdFrg.tif	CDFW	Predicted habitat suitability for the Foothill yellow-legged frog.	2016/09/14	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/07	Metadata
HardHead.shp	CDFW	Range of Hardhead by HUC-12 watersheds from CWHR (PISCES derivative).	2014/03/01	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/13	Metadata
Pacific_Lamprey.shp	CDFW	Range of Pacific Lamprey by HUC-12 watersheds from CWHR (PISCES derivative).	2014/03/01	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/13	Metadata
Riffle_Sculpin.shp	CDFW	Range of Riffle Sculpin by HUC-12 watersheds from CWHR (PISCES derivative).	2014/03/01	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/13	Metadata
SierraNevYlwLgdFrg.tif	CDFW	Predicted habitat suitability for the Sierra Nevada yellow-legged frog.	2016/09/14	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/07	Metadata
WesternPondTurtle.tif	CDFW	Predicted habitat suitability for the Western Pond Turtle.	2016/09/14	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/07	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Habitat Prioritization Datasets:						
YosemiteToad.tif	CDFW	Predicted habitat suitability for the Yosemite Toad.	2016/09/14	BIOS (Biogeographic Information and Observation System) Viewer	2020/10/07	Metadata
Infrastructure Prioritization Datasets:						
Streams_USGS.shp	USGS	Streams and conveyances.	2019/10/02	USGS National Map Downloader	2020/10/02	Metadata
CABY_Hydroelectric.shp	US Energy Information Administration	Operable electric generating plants in the United States by energy source.	2020/07/10	EIA	2021/01/19	Metadata
Res_sed_2020.xlsx	Minear and Kondolf (2009)	Initial capacity and percent capacity remaining for reservoirs in California.	2009/12/25	American Geophysical Union	2020/10/30	Metadata
Cahh10.tif	NASA Socioeconomic Data and Applications Center	Raster with number of households.	2017/05/26	NASA Socioeconomic Data and Applications Center	2020/12/10	Metadata
Plants_for_electric_powerCaliforniaconventional_hydroelectric.csv	US Energy Information Administration	Power generated in 2019 by hydroelectric plants in California.	2020/07/10	EIA	2021/01/19	Metadata
NID_Dams.shp	US Army Corps of Engineers	Dams in California.	2020/05/28	NID (National Inventory of Dams)	2020/10/5	Metadata
water_districts.shp	CA DWR	Service area of public water agencies in California.	2021/3/8	CNRA Datasets	2021/02/08	Metadata
Other Water Quality Prioritization Datasets:						
Hydraulic_Mine_Pits_of_California.shp	USGS	Compilation of boundary location polygons for 167 hydraulic mine pits located in northern California.	2016/04/26	USGS Science Base Catalogue	2021/01/29	Metadata

Dataset Name	Created by	Description of Dataset	Date Created	Website Download	Date Downloaded	Metadata
Equity Prioritization Datasets:						
TidyCensus::get_acs()	American Community Survey	California census tract data for El Dorado, Placer, Nevada Sierra, Yuba, Plumas, Amador, and Alpine Counties for the following categories: B19013_001, B03002_004, B03002_012, B03002_005, B03002_006, B03002_007, B03002_009, B03002_008.	2019/01/01	US Census Bureau American Community Survey	2021/02/25	Metadata
Pden2010_block.zip	American Community Survey	US Block Level Population Density Raster for 2010.	2016/11/17	USGS Science Base Catalogue	2021/01/25	Metadata
Fire Probability Dataset:						
RDS-2020-0016 California.zip (BP_California.tif)	US Forest Service	Continuous values of annual burn probability with a 30m pixel size within California. This dataset is part of the larger dataset -- Wildfire Risk to Communities: Spatial datasets of landscape-wide wildfire risk components for the United States.	2020/11/25	USFS Reseasrch Data Archive	2021/02/13	Metadata

Appendix 2: Fuel Reduction Prioritization Framework

FORESTS TO FAUCETS

Fuel Reduction Prioritization Framework

Stakeholders, Priorities, & Policy

Watershed Scale Priority Setting

While larger efforts are needed to increase capacity for regional fuel treatments, watershed level prioritizations allow limited resources to be used strategically to reduce wildfire impacts to drinking water supplies and ecosystem provisions.

Water is coupled with economic, environmental, and community benefits, which in turn incur additional gains, such reduced energy use and greenhouse gas emissions, wildlife habitat provisions, and drinking water security. By removing fuel where impacts of wildfire on water are greatest, avoided costs for beneficiaries can be maximized.

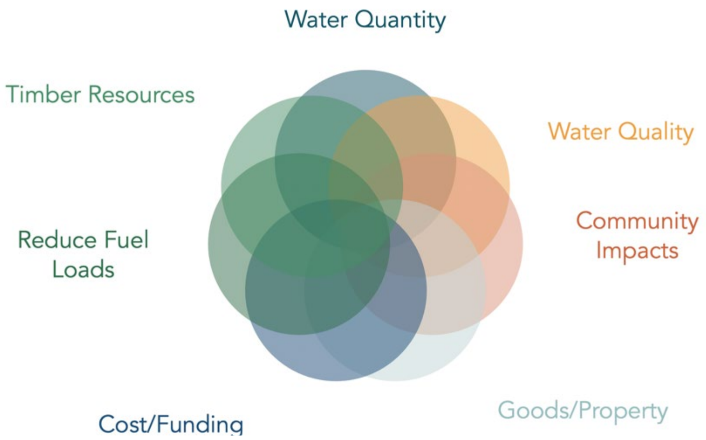


Figure 1. Common Fuel Reductions Priorities of water agencies, conservation organizations, researchers, landowners, state and federal managers and local communities.

Stakeholder Engagement

Each stakeholder comes to the table with a different mission statement and motivation for engaging in fuel reduction strategies, common shared interests are illustrated in **Figure 1**. Interviews and stakeholder meetings provide intel on socio-economic, political and ecological factors influencing the location of fuel reduction projects locally. Successful prioritizations in the Sierra Nevada Headwaters utilize collaborations amongst large landowners, water agencies, federal/state foresters and research institutions. Together they have the necessary resources to plan, fund and implement larger fuels reduction projects. In order to find common interests that can unite beneficiaries and their resources, enabling treatment of larger forest stands, common priorities can be broken down into operational outcomes, illustrated in **Table 1**. Outcomes determine who will be interested in collaborating on fuel reduction projects and inform fuel reduction location choice.

Table 1. Fuel Reduction Priorities & Outcomes.

Priority	Outcome	Priority	Outcome
Forest Resilience	Structure, composition, disturbance response,	Riparian integrity	Structure, composition, hydrologic services
Water Security	Sediment, temperature, quantity, infrastructure	Air Quality	Particulate matter, visibility, GHGs
Fire Dynamics	Severity, frequency, ecosystem services	Wetland integrity	Structure, composition, hydrologic services
Carbon Sequestration	Storage, stability	Social & Cultural Wellbeing	Public health, equitable preparedness/quality of life, engagement, recreation
Fire Preparedness	Decreased fire risk, preparedness, physical operability of landscape/suppression difficulty index	Economics	Wood products, recreation, water, systemic health, cost of forest/watershed health treatments
Biodiversity Conservation	Focal Species, species diversity, community integrity, critical habitat		

* Information adapted from Tahoe Central Sierras Initiative Forest Resilience Blueprint (2020) and interviews.

General Prioritization Considerations

In order to prioritize fuel reduction locations where treatment is feasible and likely to happen research is needed on local regulatory entities, terrain, infrastructure, weather and funding options. Fuel reduction prioritizations for federal lands involve a decentralized decision-making process informed by priorities of individual forest managers. Overarching priorities of federal land managers include proximity to human infrastructure, budget, fuel loading, deviation from historic fire regime, ecological objectives, convenience, accessibility, and weather conditions. Federal lands account for a large percentage of land in each state and have a large impact on regional forest landscapes. **Figure 2** outlines state and Federal regulations influencing fuel reduction prioritizations.

Models aid visualization of feasibility constraints and fire impacts to fuel reduction locations. Common ecological processes modelled to identify fuel reduction locations include fire risk, fuel reduction impacts, erosion and climate. Models more accurately predict impacts of fuel reduction when wildfire revisits the landscape and are less accurate when predicting wildfire impacts with no interventions. Uncertainty of models should be considered when interpreting results.

Hydrocentric Prioritization Considerations

When prioritizing fuel reduction to protect water supply and quality, regulatory frameworks have ecological consequences. For example, the Forest Practice Rules inform whether fuel reduction occurs in or near riparian areas and influence fire risk present for many rivers and streams in the United States. Riparian areas, without fuel reductions, can act as a if fuel builds up in riparian corridors endangering critical habitat areas vulnerable to the impacts of severe wildfire: reduced canopy and increased water temperatures, increased sediment, debris and contaminants.

In order to prioritize fuel reduction to minimize hydrocentric post-fire impacts the following data is needed: detailed topography (specifically geologic formations which produce deep, erodible soils), soils maps, probability of high intensity rain, local critical infrastructure, likely ignition nodes and slope. Layered in a geospatial model, this data allows managers to identify sites with deep, erodible soils, high rain intensity, southwest/northeast aligned canyons in close proximity to ignition nodes (downwind of potential sediment sources), near critical water infrastructure and surrounded by slopes greater than 30%.

State and Federal Laws Relevant to Freshwater Ecosystem Management

California Porter-Cologne Act + Federal Clean Water Act: *These statutes require the State Water Board and the Regional Water Quality Control Boards to develop water quality control plans that define water quality objectives and protect various uses, including fish and wildlife. The Forest Practice Rules (FPRs),* established guidelines for forest management of public lands, *followed by federal and state forest managers, are based on these statutes. FRBs require a Timber Harvest Plan to be reviewed by State and Regional Water Resources Boards.*

Section 5937 of California Fish and Game Code: *This statute requires dam operators to release sufficient water to keep fish below the dam in good condition. This is a clear (but often ignored) legislative directive to release enough water to support healthy fish populations. This may have a role in ensuring cold and high-quality water for ecosystem services by holding owners of water infrastructure partially liable for impacts from wildfires (which include reduced canopy and increased water temperatures as well as increased sediment, debris and contaminants).*

Public Trust Doctrine: *This doctrine protects the public's rights in navigable waters and submerged lands. Traditionally, this included navigation, commerce, and fishing, but it was later expanded to include recreational uses, water quality, and protection of ecosystems. Water-right holders and water managers must protect public trust values, which can include protecting instream flows and water quality for fish and wildlife.*

California and Federal Endangered Species Act: *The state and federal endangered Species Act (ESA) prohibit the "taking" or harming of species determined to be at imminent risk of extinction (i.e., listed as threatened or endangered) without a permit. Federal agencies are required to consult with the US Fish and Wildlife Service to ensure that their actions do not jeopardize the continued existence of listed species or adversely modify their critical habitat.*

Figure 2. State and Federal Laws important to Freshwater Ecosystem Management. Adapted from Mount et. al. (2017). Managing California's Freshwater Ecosystems.

Appendix 3: Online WEPP Erosion Tool Instructions

Guidelines for using the Online WEPP-Disturbed Watershed Tool to Support Wildfire-Induced Erosion Analysis

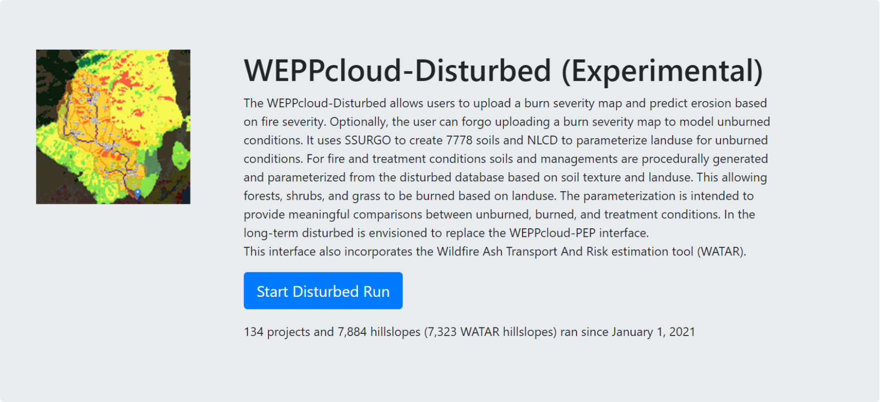
Prepare a Log/Data Folder

1. Make a project directory for your model runs in the desired location
2. Open a new word document to serve as a run log

Access the Online WEPPcloud website [https://wepp.cloud/weppcloud/]

3. Register for an account on the upper left corner of the screen, or, sign-in if already registered.

4. On the WEPPcloud landing page, scroll down to the **WEPPcloud-Disturbed** tool. Click Start Disturbed Run



WEPPcloud-Disturbed (Experimental)

The WEPPcloud-Disturbed allows users to upload a burn severity map and predict erosion based on fire severity. Optionally, the user can forgo uploading a burn severity map to model unburned conditions. It uses SSURGO to create 7778 soils and NLCD to parameterize landuse for unburned conditions. For fire and treatment conditions soils and managements are procedurally generated and parameterized from the disturbed database based on soil texture and landuse. This allowing forests, shrubs, and grass to be burned based on landuse. The parameterization is intended to provide meaningful comparisons between unburned, burned, and treatment conditions. In the long-term disturbed is envisioned to replace the WEPPcloud-PEP interface.
This interface also incorporates the Wildfire Ash Transport And Risk estimation tool (WATAR).

134 projects and 7,884 hillslopes (7,323 WATAR hillslopes) ran since January 1, 2021

5. In the upper bar, type in a unique name for your run that would be easy to locate and reference later, if needed. Click Set Name. You can return to a previous project under your account by finding it under the 'Runs' tab in the upper right corner of the screen.

Watershed Setup

6. Scroll down to Upload Soil Burn Severity Map and click Browse
   a. Navigate to where your reclassified burn severity raster is saved and click Open
   b. Click Upload SBS
7. Confirm that you have uploaded the correct map, and that it is the right location.

   For this map, reset the breaks to match the burn severity categories:

   a. No Burn ≤ **0**
   b. Low Severity Fire ≤ **1**
   c. Moderate Severity Fire ≤ **2**

d. High Severity Fire ≤ **3**

e. No Data = 15

f. Click Modify Fire Classes

8. Channel Delineation:

a. Set: Minimum Channel Length (MSCL)***** to **500** ft.

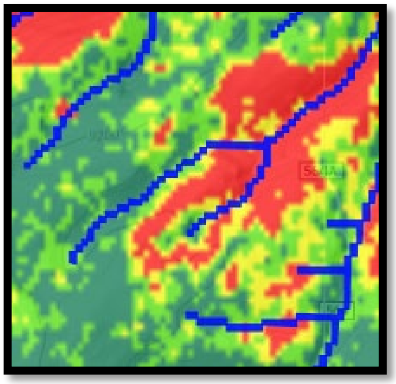
**MSCL = The shortest length that any channel is allowed to be. Input smaller value for higher resolution erosion results or larger value for coarser results.*

b. Set Critical Source Area (CSA)***** to **50** acres

**CSA = The minimum drainage area below which a permanent channel forms. Input smaller value for higher resolution erosion results or larger value for coarser results.*

c. Click Build Channels

d. When Status says "Success," scroll up to the map to see the channel network

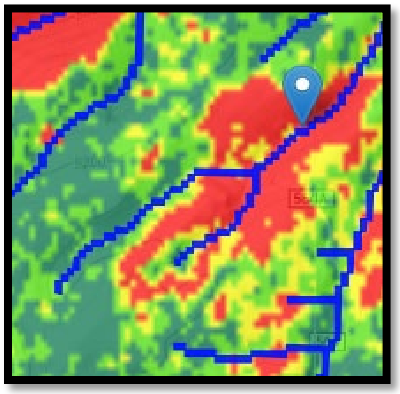


NOTE:
If you did not have the top of the watershed boundary on the screen when you clicked the Build Channels button, you will get an error when you try to build the hillslope polygons. Check the map to make sure that the top of the watershed is likely included in your map. If it is not, move the map around on the screen or zoom out until you have captured all the watershed and Click Build Channels again.

NOTE: Occasionally you will get an error message if you try to proceed to the next step without the previous step finishing.

If so, click the 'Power User' ⌘ symbol in the upper right corner and under 'Commands' click Clear Locks and make sure the previous step is completed before moving on.

9. Outlet:



a. Select ○ Use Cursor and click Use Cursor

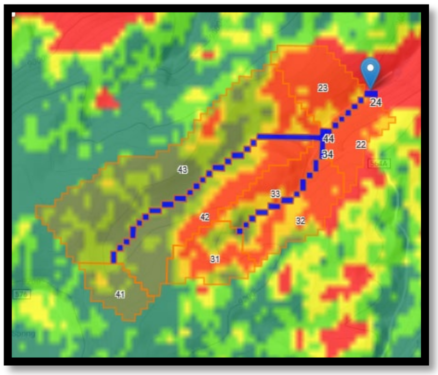
b. Scroll up to the map and click your watershed outlet. You may need to zoom in to make sure the desired pixel is selected. **Make sure the outlet point is not selected at a confluence of two channels.**

Alternate method: Select ○ Specify Lon/Lat and paste in the coordinates of the outlet point for your current run. Click Specify Lon/Lat

c. Scroll up to the map and make sure your watershed outlet is where you want it to be. You may need to zoom in to make sure the desired pixel is selected.

d. Scroll back down and note that you have been successful. The latitude and longitude of the outlet are given.

10. Subcatchments:



   a. Under Advanced Options, select 'Clip Hillslopes' and leave the default 300(m) hillslope length setting.
   b. Click Build Subcatchments
   c. Scroll up to the map and note the subcatchments or hillslopes that have been delineated. Before moving on ensure the subcatchments are fully abstracted. You will know this is complete when you see the stats of your watershed (# of slopes, # of channels, total area) under the Summary Bar.

NOTE: Make sure you don't have more than 1,000 hillslopes delineated. WEPP cannot handle more than 1,000 hillslopes. See FAQ's for more info. [https://doc.wepp.cloud/FAQ.html]

11. Land Use Options*

   a. Select ○ Determine per hillslope and click Build Landuse

12. Soil Options*

   a. Select ○ Determine per hillslope and click Build Soils

13. Climate Options*

   a. Under Select Station select ○ Multi-factor ranking. (This option considers distance, elevation, and climate in selecting the most representative climate station).
   b. Select ○ PRISM Modified as the Climate Method.
   c. For the number of years to simulate, input a value between **30-50 years.**
   d. Click Build Climate

*More information on land use, soil, and climate options & processes can be found here: [https://doc.wepp.cloud/QuickStart.html]

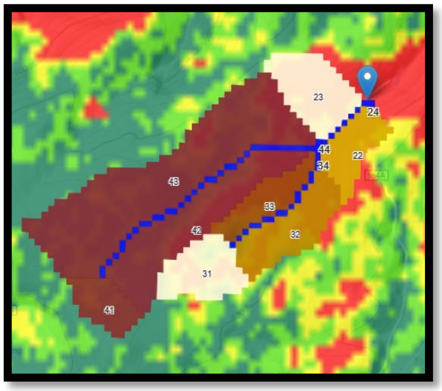
14. Save Watershed Preparation Report

   a. Under **Watershed Preparation Report**, click 'Download as CSV Zip Archive' save it in the project directory.

Running WEPP

1. Click Run WEPP

NOTE: By default, WEPP is set to run under 'watershed mode' in which the dominant landuse and soil is assigned to each hillslope. If desired, users can run flowpath processing by selecting the 'run flowpaths' option under the Advanced Options of the WEPP section. Flowpath mode calculates erosion for each pixel's assigned landuse and soil resulting in a gridded soil deposition/loss map, however, runtime is considerably longer.



2. When the WEPP run is complete:
    a. Copy and paste the project URL into your run log so you can return to the project later if needed.
    b. Under **WEPP Results**, click 'Return Periods Report.' Scroll to the bottom and copy the 'Sediment Yield' table to your clipboard by clicking the clipboard button. Paste into your run log.

Exporting

1. To export the results to display in ArcMap or other GIS tools:
    a. Click Download Zip Archive with gtiffs and shapefiles under the Export options at the bottom
    b. Click Save As and save the file in your project directory
    c. Unzip the downloaded file into the project folder. Create a new GIS project and save it in the project folder. Add the contents of the unzipped shapefile folder to the project.

2. As other watershed runs are completed in WEPPcloud, add them to the ArcMap project. Relabel layers as needed to keep track of your progress (See Appendix A)

3. To begin the next subwatershed within your area of interest click the fork project button on the top bar. Once complete, click the new URL generated under "Proceed to…*New URL*". Repeat process above starting at **Step 8: Channel Delineation**.

NOTE: The watershed will delineate differently if the map extent, TOPAZ parameters, or outlet location are changed. To get the same watershed to delineate you can manually set the center location of the map and zoom level as well as specify the longitude and latitude of the outlet.

SUPPLEMENTARY RESOURCES & TOOLS

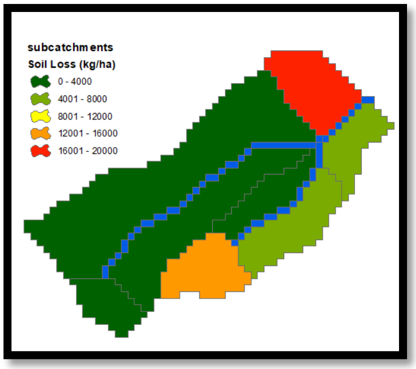
1) Importing the Results of a WEPPcloud Watershed Run into ArcMap

1. Navigate to your project directory and unzip the GIS files you downloaded:
    a. Rename the directory to something a bit more meaningful.
2. Open ArcMap:

  b. On the Open existing map screen, click Cancel.

3. In the ArcMap command lines, click the + icon:
    c. Navigate to your unzipped data directory, hold down the shift key, and select both *.shp files,
    d. Click Add.

4. Fill in some map details



    e. Change the channel color to blue
    f. Right click on subcatchments, and select "Properties":
        i. Under the Symbology tab, select Quantities:
            1. Under Quantities, select Graduated colors
            2. Change Value to SoLs(kg/ha) (Soil Loss)
            3. Under classes, enter how many you want, for example 5
            4. Change the breaks every 2000 kg/ha etc.

5. As other watershed runs are completed in WEPPcloud, add them to the ArcMap project. Be sure to relabel layers as needed to keep track of your progress.

2) Combining Multiple Watershed Runs (Outside GIS Environment)

1. Go to the main WEPPcloud page: https://wepp1.nkn.uidaho.edu/weppcloud
2. Scroll to the bottom to WEPPcloud Utilities and select Combined Watershed Viewer URL Generator.
3. Paste the run ID's you would like to combine separate by commas. The run ID's are the randomly generated phrases within the URL name. For example: https://wepp.cloud/weppcloud/runs/**invaluable-vantage**/disturbed/.
4. Optionally, you can provide a title for your combined output. Then click 'Generate URL'
5. Click on the new URL to view the combined outputs.

3) Estimating Pre-fire Erosion Rates

1. If you want to know erosion rates prior to the wildfire:
    a. Click again the Fork Run button to create a new project
    b. Scroll down to Land Use Options and select ○ Single Landuse for Watershed
        i. For all land use conditions, select Disturbed WEPP: Forest
    c. Scroll down to Soil Options,

        ii. Select ○ Single Soil for Watershed (Database)
        iii. Select Forest/Forest sandy loam.sol (or dominant texture for site)

    d. Scroll down WEPP and click Run WEPP

4) Databases Accessed by the Online Tool:

a) Google Map: Physical, Streets, Hybrid and Satellite layers

b) USGS 30m DEM

c) 30m 2011 NLCD land use layers

d) NRCS SSURGO and STATSGO soil databases

e) NSERL CLIGEN database of weather stations with monthly parameters for US Locales

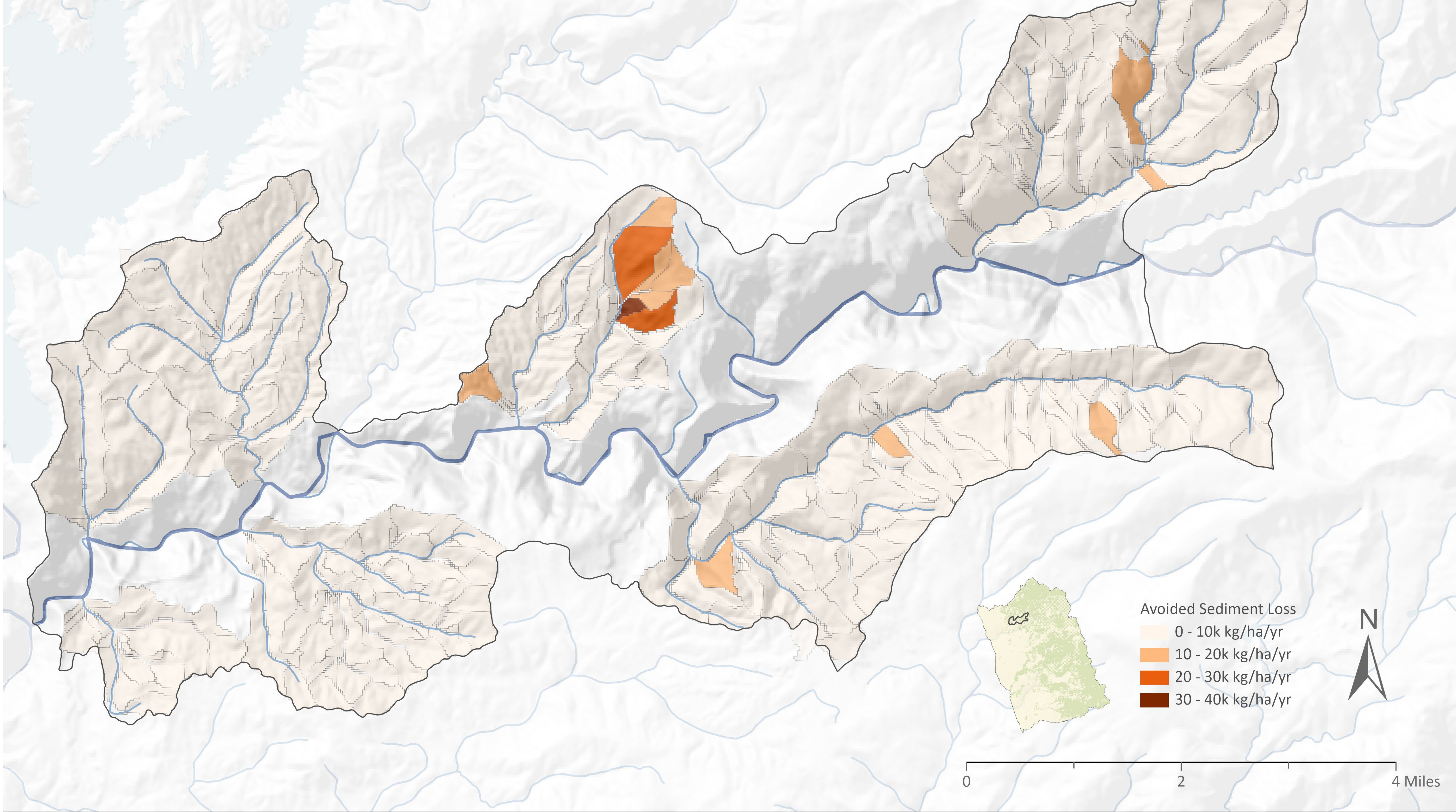
f) PRISM 800-m resolution monthly precipitation, and maximum and minimum temperatures

g) Burn Severity Raster uploaded by the user

Appendix 4: Avoided Sediment Loss Results for Recommended Watersheds

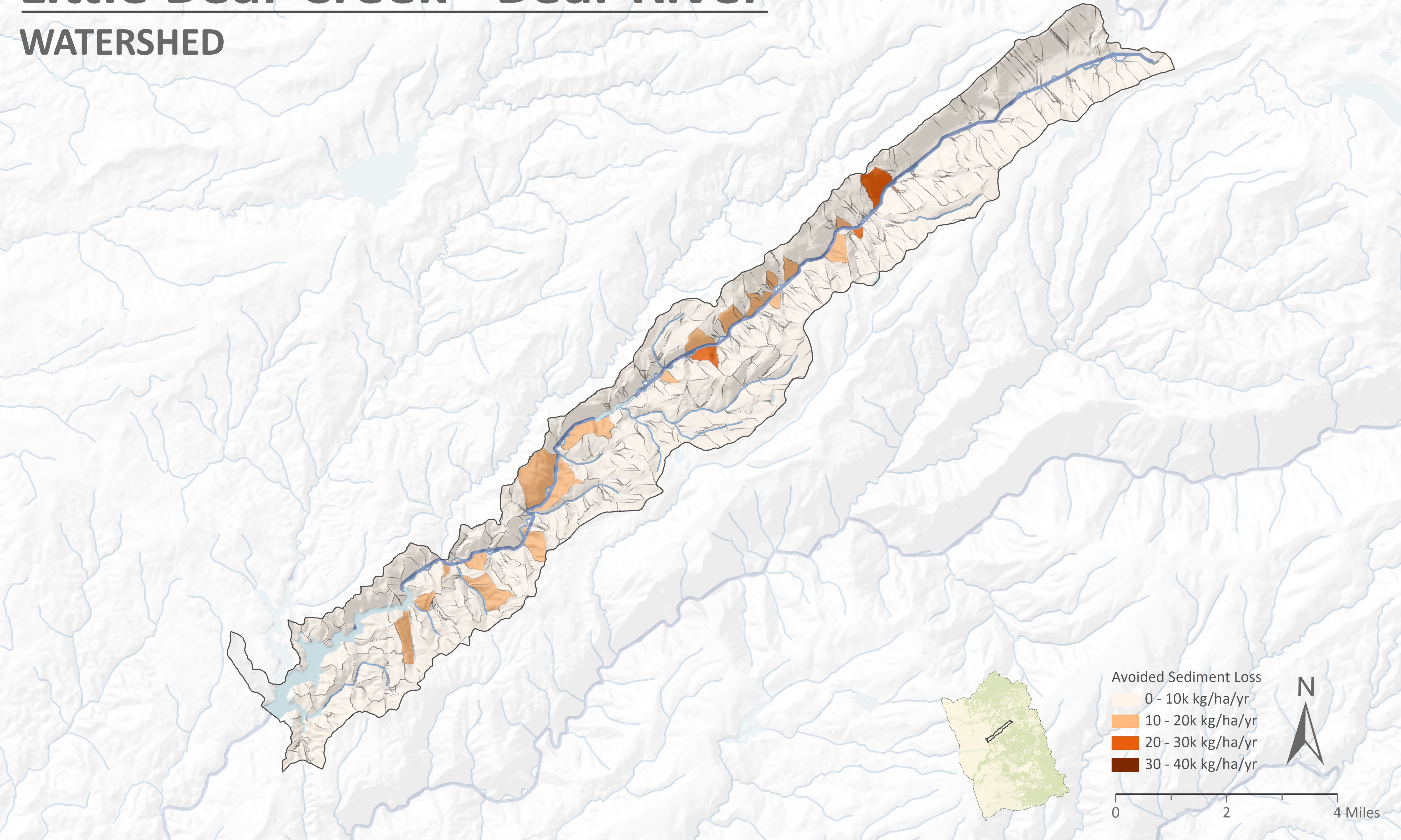
Grizzly Creek - Middle Yuba

WATERSHED



Little Bear Creek - Bear River

WATERSHED



Slate Creek

WATERSHED