MOKELUMNE WATERSHED AVOIDED COST ANALYSIS:

Why Sierra Fuel Treatments Make Economic Sense

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FOREST SERVICE U S DEPARTMENT OF AGRICULTURE

Mokelumne Watershed Avoided Cost Analysis: Why Sierra Fuel Treatments Make Economic Sense

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Disclaimer

This report is rich in data and analyses and may help support planning processes in the watershed. The data and analyses were primarily funded with public resources and are therefore available for others to use with appropriate referencing of the sources. This analysis is not intended to be a planning document.

The report includes a section on cultural heritage to acknowledge the inherent value of these resources, while also recognizing the difficulty of placing a monetary value on them. This work honors the value of Native American cultural or sacred sites, or disassociated collected or archived artifacts. This work does not intend to cause direct or indirect disturbance to any cultural resources.

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Document Review

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Support Language

Approved October 30, 2013

The Mokelumne Avoided Cost Analysis (MACA) Project is a detailed analytical study intended to inform future forest watershed planning, as well as public and private investment. The focus of the study was the potential avoided costs from fuels reduction treatments in the Mokelumne Watershed. MACA involved a Planning Team, Advisory Committee, Technical Team, and Consultant Team. Each group played a critical role in the process, with the Planning Team ultimately responsible for major project decisions and managing day-to-day project activities; the Advisory Committee providing strategic advice on key decisions and improving the project design and draft analyses; the Technical Team advising on decisions regarding the analytical, modeling, and other technical components of the project; and the Consultant Team taking the lead in developing the analysis. The Advisory Committee met every two to three months, with the Technical Team meeting in between Advisory Committee sessions, the Planning Team meeting bi-weekly, and the Consultant Team having regular interaction with all other groups.

As part of the Advisory Committee, the following managers, executives, and representatives contributed their experience, committed their technical staff, data, information, and, in some cases, committed their organization's resources to support the project. The Advisory Committee partnered with the sponsors on each aspect of the collaborative process, including identifying key issues for analysis; providing strategic advice on key design choices, and feedback on initial work products; developing communication strategies, messages, and materials; sharing key project milestones with their constituencies; and reviewing the draft chapters that constitute this report. The Committee operated under a consensus-seeking decision-making protocol, where each member shared information, sought to understand the range of interests, and worked to develop solutions that met these interests to the maximum extent possible.

The following participants support the findings and conclusions in this report.

- Sierra Nevada Conservancy: Kim Carr and Nic Enstice
- The Nature Conservancy: David Edelson and Kristen Podolak
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- California Department of Water Resources: Eric Hong
- California Department of Forestry and Fire Protection: Bill Snyder, Chris Keithley, and Dave Sapsis

- East Bay Municipal Utility District: Richard Leong
- Environmental Defense Fund: Ann Hayden
- Foothill Conservancy: Katherine K. Evatt, R. Winston Bell, Jr., and Reuben Childress
- Forest Service, Eldorado National Forest: Kathy Hardy, Laurence Crabtree, and Rick Hopson
- Forest Service, Stanislaus National Forest: Susan Skalski and Teresa McClung
- Native American representative: Fred Velasquez
- Sierra Pacific Industries: Mark Luster and Tim Tate
- Sustainable Conservation: Kelli McCune and Daniel Mountjoy
- West Point Fire District: Jim Carroll

Table of Contents

Abbreviations and Acronyms

ACCG – Amador Calaveras Consensus Group

AU – Analysis Units

BLM – Bureau of Land Management

BP – Burn Probability

CO_{2e} – Carbon Dioxide equivalent – refers to the potency of other greenhouse gases as they relate to Carbon Dioxide

CSO – California Spotted Owl

EBMUD – East Bay Municipal Utility District

ERC – Energy Release Component (Element of the fire modeling)

FERGI – Fire-Enhanced Runoff and Gully Initiation (Model)

FRI – Fire Return Interval

FSim – Fire SIMulation system (Model)

GeoWEPP – Geospatial update to the Water Erosion Prediction Project (Model)

GHG – Greenhouse Gas

Ha – Hectare

IRWM – Integrated Regional Water Management

IU– Influence Unit

MACA – Mokelumne (watershed) Avoided Cost Analysis

NPV – Net Present Value

PAC – Protected Activity Center

PG&E – Pacific Gas & Electric

PostT – Post-treatment

PreT – Pre-treatment

PR – Pardee Reservoir

SPLAT – Strategically Placed Landscape Area Treatments

TAU– Treated Analysis Units

TCAB – Tiger Creek Afterbay

WUI – Wildland Urban Interface

Models that were used

A2 – From the Global Climate Models – Scenario A2 assumes that our society will make only minor changes to our current technologies and practices and emissions of GHGs will continue to increase at a pace our current rate.

B1 – From the Global Climate Models – Scenario B1 assumes a significant global reduction in worldwide GHG emissions, with the peak in global carbon emissions reached around 2050 and then declining back to carbon emission rates of the 1970s.

FERGI – Fire-Enhanced Runoff and Gully Initiation - Sediment – Appendix E

FlamMap – Fire – Appendix A

FSIM – Fire – Fire SIMulation system - Appendix A

GCM – Global Climate Models – Chapter 9

- PCM – Parallel Climate Model
- GDFL – Geophysical Fluid Dynamics Laboratory Model

GeoWEPP – Sediment –Geospatial update to the Water Erosion Prediction Project – Appendix C

Conversion Table

1 hectare (ha) = approximately 2.5 acres (ac)

1 tonne (metric ton) = 1 Megagram (Mg) = approximately 2205 pounds

1 acre-foot (a-f) = 325,851 gallons = 1,233 cubic meters (m^3) = ½ of an Olympic pool

1 Megawatt (MW) = 1,000 kilowatts (kW) = 1,000,000 watts

Executive Summary

High-severity wildfires in forests of California's Sierra Nevada pose a serious threat to people and nature. Although proactive forest management can reduce the risk of high-severity wildfire, the pace and scale of fuel treatments is insufficient, given the growing scope of the problem. Using the upper Mokelumne River watershed as a representative case, we sought to answer the following question: Does it make economic sense to increase investment in fuel treatments to reduce the risk of large, damaging wildfires? Our analysis suggests that the economic benefits of landscape-scale fuel-reduction treatments far outweigh the costs of wildfire.

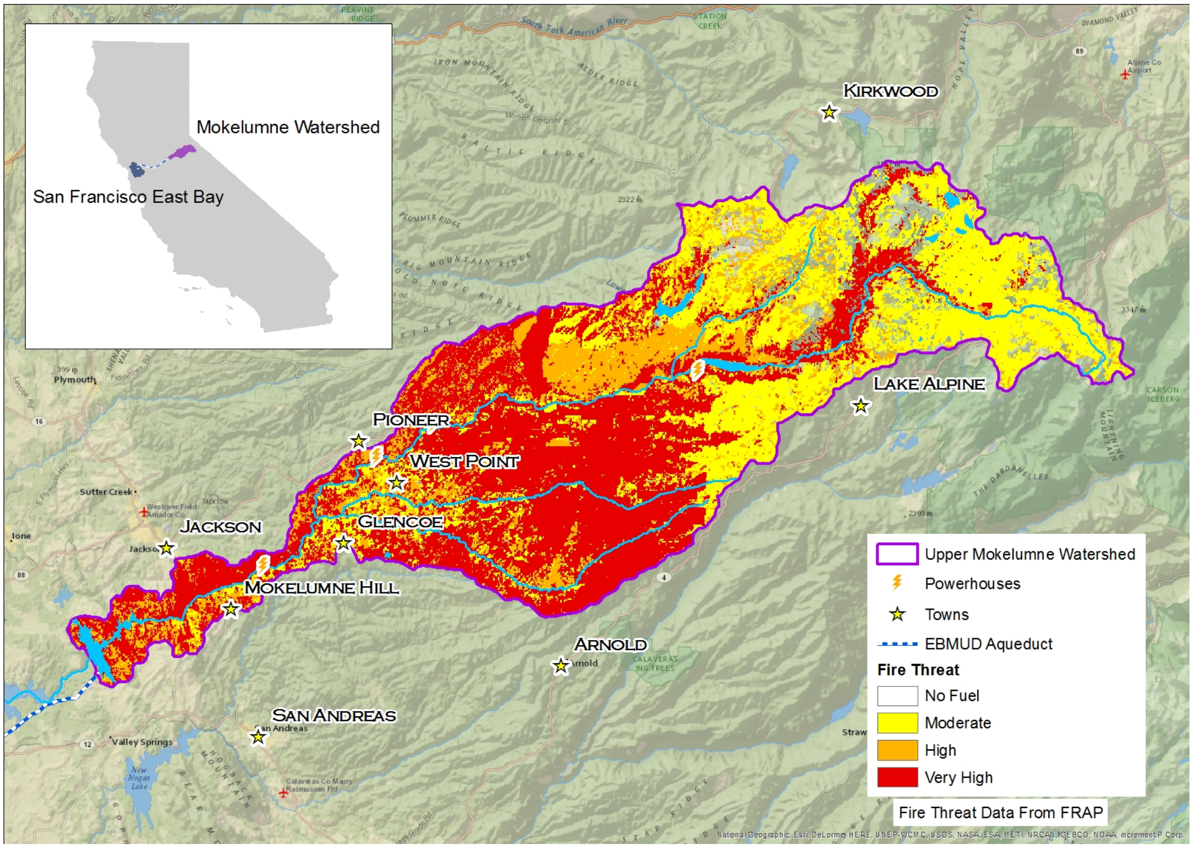
Recent wildfires in California and the West have destroyed lives and property, degraded water quality, put water supply at risk, damaged wildlife habitat and cost hundreds of millions of dollars. For example:

- The 2013 Rim Fire – located just south of the Mokelumne River in the central Sierra Nevada – burned nearly 257,000 acres, much of it at high intensity, at a cost of more than $127 million, not including the costs to the economy and tourism.
- The 2013 Yarnell Fire in Arizona killed 19 firefighters, destroyed more than 100 homes and damaged the town's water system.
- The 2002 Hayman Fire in Colorado burned 138,000 acres, destroyed more than 600 structures, and deposited more than 1 million cubic yards of sediment into Strontia Springs Reservoir — a primary drinking water source for the City of Denver — at a growing cost of more than $150 million.

The Sierra Nevada provides more than 60 percent of the developed water supply for California. High-severity wildfire places this water supply at risk. The upper Mokelumne River watershed in the central Sierra Nevada supplies drinking water to 1.3 million residents of the San Francisco Bay Area and provides valuable goods and services, including but not limited to forest and agricultural products, hydropower energy, recreation, wildlife habitat and carbon sequestration. Like other Sierra Nevada and western watersheds, much of the Mokelumne watershed is at very high risk of wildfire (Figure ES-1).

Although wildfire and the associated costs are increasing in the western United States, few studies have taken a hard look at the costs and benefits of fuel treatments to determine if an increased investment in treatments makes economic sense. Through a collaborative process with key stakeholders and using state-of-the-art models for fire, vegetation and post-fire erosion, we analyzed the potential impacts of a landscape-scale fuel treatments program in the upper Mokelumne watershed. In addition, we examined who would benefit the most from investing in fuel treatments and reducing the risk of high-intensity wildfires. Our findings can help inform forest management not only in the Mokelumne watershed, but also in similar watersheds throughout the Sierra Nevada and the western United States.

Figure ES-1. Fire hazard in the upper Mokelumne watershed



ES.1 Process

In February 2012, the Sierra Nevada Conservancy, The Nature Conservancy, and the U.S. Forest Service convened a diverse group of stakeholders to consider whether an economic case could be made for increased investment in fuel reduction in the upper Mokelumne watershed. This group included land managers (the Forest Service, Bureau of Land Management and Sierra Pacific Industries); water and electric utilities (East Bay Municipal Utility District, Pacific Gas & Electric); state and local agencies (California Department of Water Resources, California Department of Forestry and Fire Protection and county governments); environmental organizations (Sustainable Conservation, Environmental Defense Fund); and local stakeholders (Foothill Conservancy, Amador-Calaveras Consensus Group, West Point Fire District).

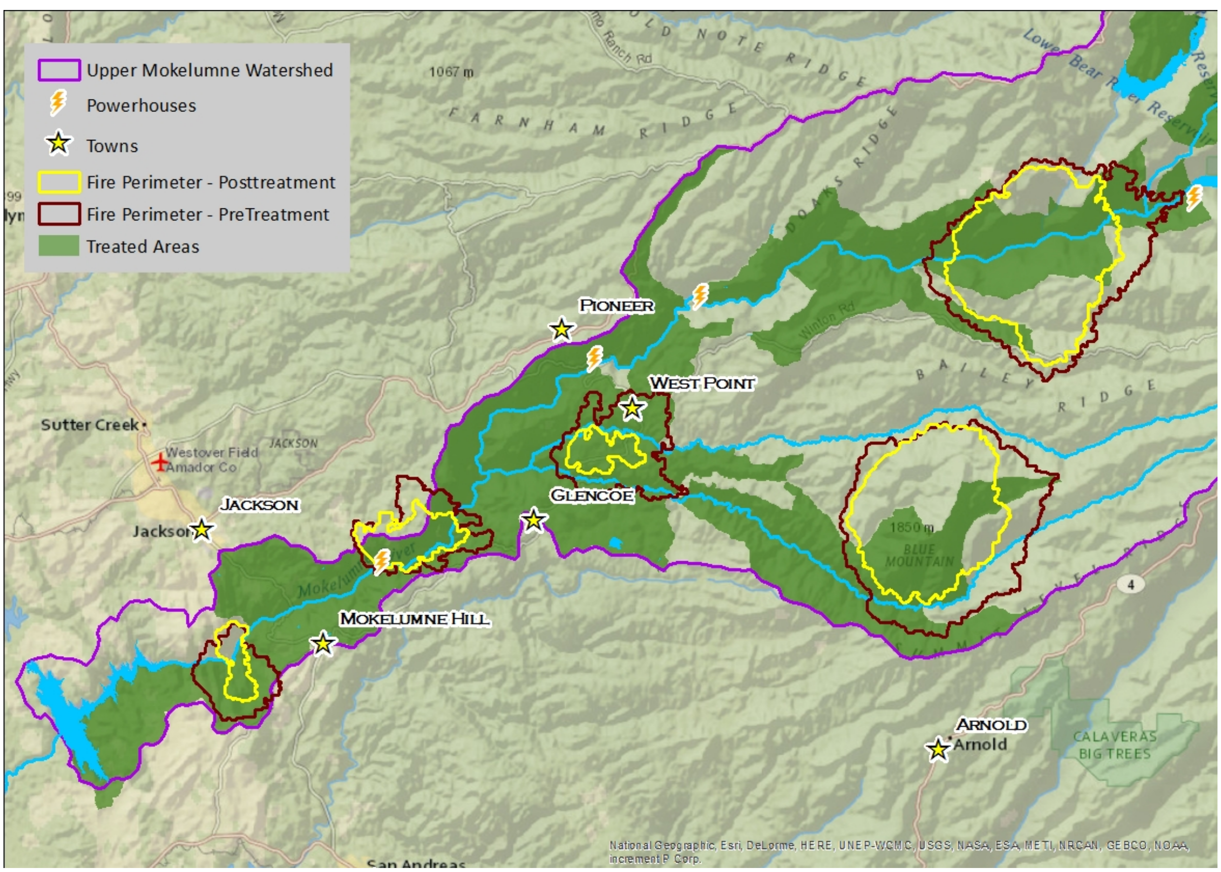
We established an Advisory Committee to help guide the overall process and analysis, a Technical Committee to address issues relating to science and modeling, and a consulting team, led by ECONorthwest, to conduct the economic analyses. Using a collaborative process, we developed a site-specific fuel-treatments scenario, targeting areas of high fire risk to homes, communities and utility infrastructure, as well as post-fire sediment erosion risk to waterways. We commissioned studies to simulate the outcomes of future fires with and without fuel treatments — specifically forest thinning and controlled burning. The Advisory Committee, Technical Committee, and consultants subsequently reviewed the analysis, vetted and approved each chapter of the report and endorsed the report's findings and conclusions.

ES.2 Analysis

Our analysis focused on modeling wildfire in the Mokelumne watershed both with and without implementation of the fuel-treatments scenario. We analyzed the size and intensity of five potential representative fires based on fire history in the region, current forest conditions and state-of-the-art wildfire models. We modeled the fuel-treatments scenario to identify how active forest management would likely modify wildfire behavior and post-fire erosion over a 30-year time period. Using these results, we quantified the financial costs and benefits of the treatments, focusing on those elements to which a dollar value can readily be assigned such as homes, infrastructure, timber, biomass energy, carbon and employment.

The analysis was based on conservative assumptions regarding potential costs and benefits, not a worst-case wildfire scenario. For example, the nearby 2013 Rim Fire was significantly larger than all five modeled fires combined and burned at higher intensity. In addition, we did not consider wildfire impacts with economic values that could not be readily determined, such as the effects of fire on wildlife habitat, recreation, tourism, and public health and cultural sites. Thus, in multiple respects, our conclusions likely underestimate the costs associated with future wildfires and the benefits of active management, suggesting an even stronger case for action.

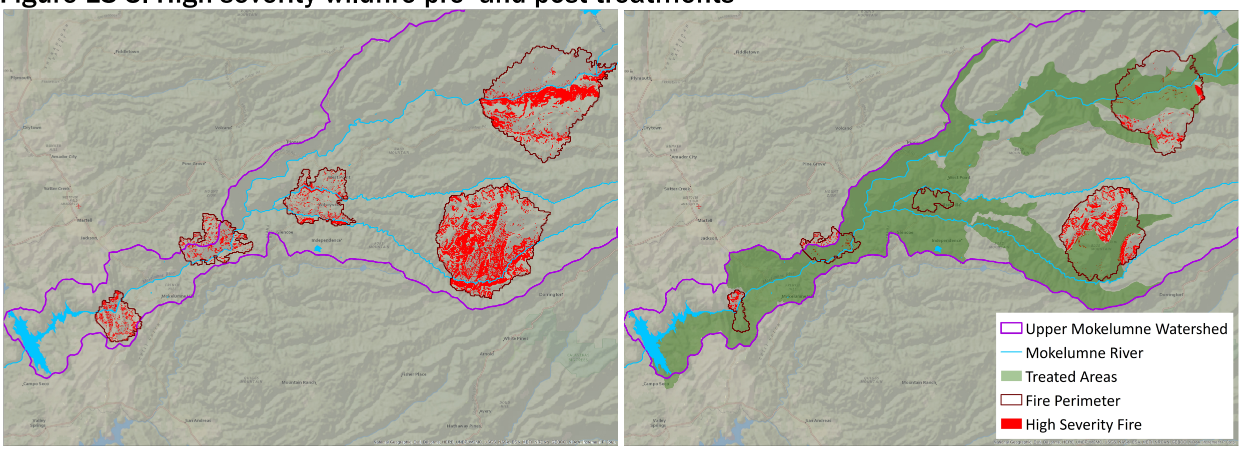
Figure ES-2. Fire perimeter reductions due to treatments



ES.3 Key Findings

- Fuel treatments can significantly reduce the size and intensity of wildfires. Proactive forest management can significantly modify fire behavior by reducing fire intensity, size and rate of spread. Our results showed that the modeled fuel-treatments scenario reduced the size of each of the five fires by 30 to 76 percent, or a total reduction in size of approximately 41 percent (Figure ES-2). More importantly, the modeled scenario reduced the acreage of high-intensity wildfire by approximately 75 percent (Figure ES-3).

Figure ES-3. High-severity wildfire pre- and post-treatments



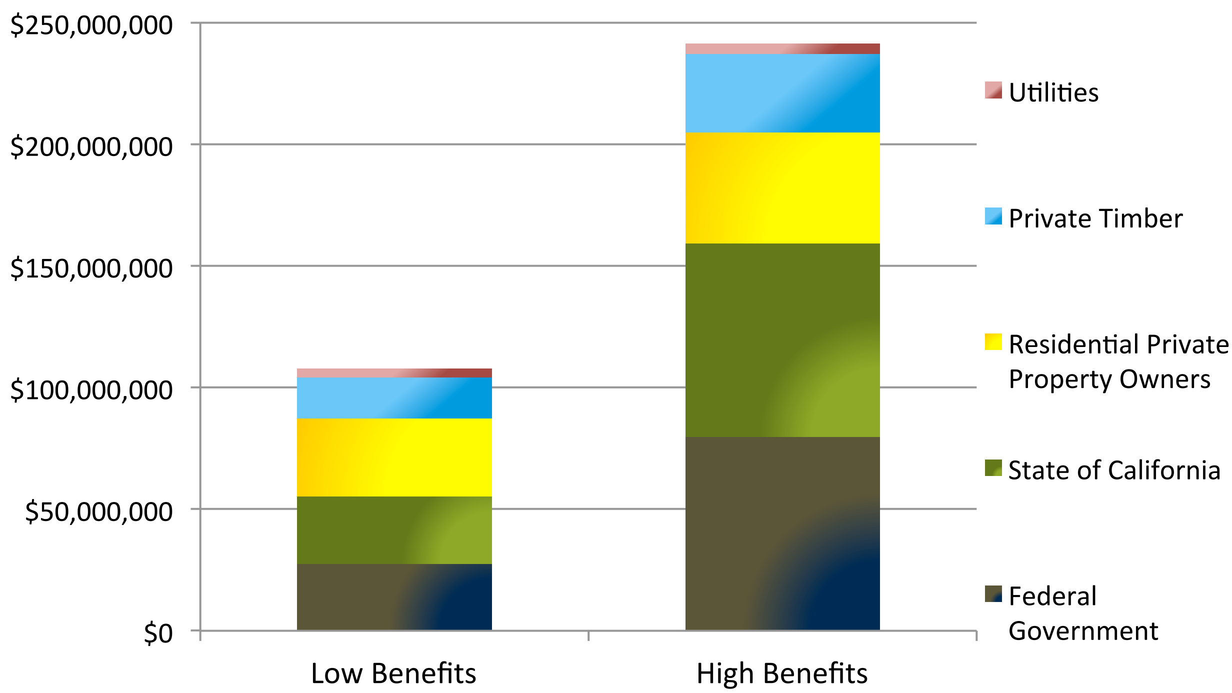
- The economic benefits of fuel treatments may be three or more times the costs. In total, across the categories of benefits quantified in this report, the value of avoided costs significantly exceeds the cost of fuels management (Figure ES-4). The avoided losses in terms of both costs and lost income opportunities include the value of structures saved from wildfire and the costs of fire suppression and post-fire restoration, as well as potential revenue from carbon sequestration, merchantable timber and biomass that could be used for energy. For each cost category, we estimated a range of values from low to high. Using the high estimates for benefits ($224 million) results in a benefit-cost ratio for the fuel-treatments scenario of 3.3:1. Even when applying a more conservative approach, using the low estimate for benefits ($126 million), the benefits of investing in fuel treatments are nearly twice the costs, with a benefit-cost ratio of approximately 1.9:1.

- There are many beneficiaries from increased fuel treatments, especially taxpayers. The economic benefits of fuel treatments accrue to a wide range of landowners, public and private entities, taxpayers and utility ratepayers. As shown in figure ES-5, the primary beneficiaries are the State of California, federal government, residential private property owners (and their insurers), timber owners, and water and electric utilities. By comparison, the costs of fuel treatments are largely borne by public land managers (and, by implication, taxpayers). An accelerated fuel-treatments program would also result in an estimated 35-45 jobs relating to fuel treatments and 7-10 biomass-to-energy jobs over a 10-year period. These figures represent a significant addition to the current number of such jobs in these rural areas.

Figure ES-4. Total costs and benefits for fuel-treatments scenario

Costs		
Fuel Treatment	$68,000,000[1]	$68,000,000
Benefits	*Low*	*High*
Structures Saved	$32,000,000	$45,600,000
Avoided Fire Cleanup	$22,500,000	$22,500,000
Carbon Sequestered	$19,000,000	$71,000,000
Merchantable Timber from Treatment	$14,000,000	$27,000,000
Avoided Suppression	$12,500,000	$20,800,000
Biomass from Treatment	$12,000,000	$21,000,000
Avoided Road Repairs and Reconstruction	$10,630,000	$10,630,000
Transmission Lines Saved	$1,600,000	$1,600,000
Timber Saved	$1,200,000	$3,130,250
Avoided Sediment for Utilities (water supply)	$1,000,000	$1,000,000
Total Benefits	*$126,430,000*	*$224,260,250*

Figure ES-5. Fuel-treatments beneficiaries



[1] Although our analysis was based upon a $68 million fuel-treatments scenario, the local land managers estimate that many, if not all, of the benefits could be achieved at a lower cost of $16 million (see Chapter 7). To reflect a conservative approach, we have not used this lower cost figure in calculating the benefit-cost ratio of implementing the fuel-treatments program.

In sum, our analysis shows that it makes economic sense to invest in forest management to reduce the risk of destructive, high-severity wildfires in the upper Mokelumne Watershed. Although achieving such benefits requires a significant increase in funding to achieve the appropriate pace and scale of fuel treatments, the long-term cost savings far exceed the costs of the initial investment. To the extent that the Mokelumne is representative of other fire-adapted forested watersheds of the Sierra Nevada and the western United States, this report makes the economic case for significantly increasing investment in fuel treatments in western forests.

Chapter 1: Introduction

1.1 Introduction and Context

Sierra Nevada watersheds provide a wide range of benefits for people and nature. Many of these benefits, like clean water and clean air, do not have an accepted market value and therefore are not readily considered in decisions regarding how watersheds are managed. By rigorously quantifying the "ecosystem services" provided by healthy watersheds, we can begin to incorporate these important values into land and water management decisions and investments.

The forests of the Sierra Nevada, like many forests throughout the western United States, are overly dense with small trees and brush and are at risk of uncharacteristic, high-severity wildfires. Megafires, like the 2013 Rim Fire that burned into Yosemite National Park, threaten lives and property as well as a host of values, including wildlife habitat, water quality, carbon storage, recreation, and timber. Fuel reduction activities, like mechanical thinning and controlled burning, can modify fire behavior, but the pace and scale of fuel treatments are insufficient given the magnitude of the problem.

Using the Mokelumne watershed as a test case, this study addresses the following question: Does it make economic sense for society to increase investment in fuel reduction in Sierra Nevada forests, taking into account the broad range of benefits that such activities provide?

The Mokelumne River is located on the western slope of the north-central Sierra Nevada. In addition to being a primary tributary for the Sacramento-San Joaquin River Delta, the Mokelumne River produces 215 MW of hydropower capacity, provides 1.3 million San Francisco East Bay residents with their drinking water, and supplies water for agricultural and municipal purposes. The primary utilities in the watershed that provide these services are the East Bay Municipal Utility District (EBMUD) and Pacific Gas & Electric (PG&E). The watershed also holds extensive forest stands under public and private ownership, including the U.S. Forest Service (USFS), Bureau of Land Management (BLM), and Sierra Pacific Industries. Like other Sierra watersheds, the Mokelumne watershed has experienced fires in the last few decades, including the 2004 Power Fire, and is at risk of even larger and more severe wildfires in the future.

This report details the process and results of a collaborative project that combined stakeholder input with scientific and economic analysis to quantify the risks and costs associated with wildfire in the upper Mokelumne River watershed. These costs, which recent fire seasons in the West have demonstrated can be in the tens to hundreds of millions of dollars per fire, are weighed against the potential benefits provided by strategically placed forest fuel treatments in high-fire-threat areas.

To investigate the value of investing in fuel treatments, a broad group of stakeholders came together, with leadership from the Sierra Nevada Conservancy, USFS, and The Nature Conservancy, to conduct research into the benefits and costs of a strategy to accelerate fuel treatments implementation in the watershed for the purpose of reducing wildfire risk and the risk of postfire erosion. This report details that effort and the variety of biophysical and economic modeling and analyses used to answer the question: "what future costs can be avoided by treating the upper Mokelumne River watershed to reduce the risk of wildfire?"

This project involved many stages of analysis, all of which included review and input from a wide variety of public and private stakeholders, including public and private landowners, utilities and businesses, environmental organizations, local residents, and regulatory agencies. We undertook studies to simulate the locations and severity of future wildfire in the watershed with and without fuel treatments and to project how those modeled wildfires would affect local and regional assets both from direct fire damage and from postfire erosion and debris flows into downstream reservoirs and other watershed infrastructure. We considered the economic value of resources affected directly by wildfire and indirectly by the subsequent erosion and sediment effects. We attempted to identify not only what these potential costs might be, but also who the beneficiaries would be.

The chapters of this report describe the methods and results for the full series of analyses necessary to arrive at a rigorous and scientifically valid set of data describing the costs and benefits of fuel treatments in the upper Mokelumne. Subsequent chapters typically rely upon results from preceding chapters. The final results are presented in terms of economic values for these effects and the distribution of effects, while interim chapters provide details on the methodology and quantitative results of fire, erosion, and sediment modeling efforts. The appendices (A-J) provide additional details regarding the modeling efforts and other analyses processes.

1.2 Wildfire Risk and Effects

Wildfire can increase the subsequent severity of flooding and erosion in watersheds, as well as the introduction of nutrient and metal contaminants to waterways (Writer 2012). Throughout the West, observed postfire erosion levels have been observed to be multiple times, or even orders of magnitude, greater than prefire conditions (e.g., Badia 2008; Caroll 2007; Mayor 2007). Additionally, while the West has experienced more dramatic fire seasons, fuel-thinning treatments have demonstrated their value in reducing the extent of infrastructure damage around where they are implemented.

As science provides better understanding of the economic value of services functional watersheds provide, communities are better able to quantify the cost savings from investing in green infrastructure as opposed to traditional gray infrastructure such as water treatment plants. Watersheds provide valuable water supply and water quality treatment to communities across the country, and the value of these services is well documented. New York City famously saved billions of dollars through a $1.5 billion investment in watershed protection, and many cities, including Boston, Seattle, and Portland, OR, are also avoiding hundreds of millions of dollars in water treatment costs through heightened watershed protection (Postel 2005). This premise also extends to preventative efforts, rather than after-the-fact repairs, reconstruction, and clean-up, as demonstrated with the Wallow Fire in Arizona.

Communities are recognizing the benefit of directly investing in efforts to reduce wildfire risk. Denver Water provides drinking water to 1.3 million people in the Denver metropolitan region from a variety of surface water sources and is investing in actions aimed at reducing the wildfire risk that threatens those sources. One of these sources is Strontia Springs Reservoir, which received over a million cubic yards of sediment runoff from storms that followed the 11,900-acre Buffalo Creek Fire (1996) and the 138,000-acre Hayman Fire (2002) (Denver Water 2013). The runoff led to increased levels of manganese in the reservoir, which required Denver Water to increase chlorine treatment to mitigate the problem, ultimately leading to higher treatment costs (Moody 2013). Denver Water has spent over $26 million on water quality treatment, sediment removal, and infrastructure improvements as a result of the two fires (Denver Water 2013). To prevent further degradation of water quality and loss of reservoir storage capacity, Denver Water has partnered with USFS to invest $16.5 million each over 10 years for forest fuel treatments in source water areas.

The city of Santa Fe, New Mexico, has similarly taken a closer look at its water supply's vulnerability to wildfire in the wake of a series of fires in 2000 and 2001 that were near the forests that supply their water. In 2002, the city established the Santa Fe Municipal Watershed Project with USFS, The Nature Conservancy, and local groups to implement an $8 million fuel treatments project (City of Sante Fe 2013). More recently the city established the Watershed Investment Plan, which directs $220,000 per year from water utility ratepayers to fund fuel treatment and related activities. The city estimates that the investment of $5.1 million in forest fuels treatments in its water source watershed should result in avoided sediment dredging costs from the city's reservoirs of $80 to 240 million (City of Sante Fe 2013).

The city of Bend, Oregon, like many other communities relying on surface water, must comply with the Long-Term 2 Enhanced Surface Water Treatment (LT2) rule under the Safe Drinking Water Act and treat water for cryptosporidium.[1] While ultraviolet treatment is the lowest cost treatment option, the Bend city council voted to invest instead in membrane filtration because they expect a wildfire to introduce sediment loads to the surface water supply in the near future and ultraviolet treatment alone would render the sediment-laden surface water unusable. The ultraviolet treatment over 20 years would cost roughly $20 million, while membrane filtration over the same time period will cost over twice that ($42 million or more), for a cost imposed by the risk of wildfire of over $20 million (City of Bend 2013).

In 2004, a partnership with diverse stakeholders was reached in the Apache-Sitgreaves National Forests to begin a 10-year stewardship program in Arizona (The Nature Conservancy 2010). The stated project goals were to "reduce the impact of wildfires to communities at risk, to improve wildlife habitat, and to restore forest health, while helping rural communities stimulate employment in the wood products industry." By 2010, 35,166 acres of land had been treated and an additional 14,553 acres were in the process of being treated that year. One year later, in 2011, the Wallow Fire burned over 500,000 acres and was the largest fire in the history of Arizona (Graham 2011). The fire threatened a number of communities, including Alpine and Greer. As part of the stewardship program, defensible zones were created around communities and many

[1] For details on the LT2 rule see U.S. EPA, 2013. Long Term 2 Enhanced Surface Water Treatment Rule. http://water.epa.gov/lawsregs/rulesregs/sdwa/lt2/index.cfm.

credit those treated areas for saving those communities (Keller 2011). As the fires reached the treated zones, they dropped from the crown to the ground and the flame length diminished enough to allow firefighters to attack the fire. All the structures in these towns but one survived the fire. Without the treatments, the property and structural damages, as well as economic costs, would have been significantly greater.

Mechanisms for financing watershed protection projects include the full range of public financing options, including taxes on fuel and general sales, fees on utility services, taxes on utility revenues, joint public-private enterprises, general tax revenues and bond measures, and voluntary contributions (Postel 2005). In theory, the most appropriate financing mechanism is designed so that those who benefit are also those who pay the costs, and in some cases the revenue from biomass or timber removed during fuel treatments activities can help alleviate the costs. As such, funding for fuel treatments and watershed protection efforts should be designed based on when, how, where, and to whom the costs and benefits occur.

1.3 Mokelumne Watershed Physical and Socioeconomic Characteristics

The upper Mokelumne River watershed spans 885 square kilometers across Alpine (pop. 1,102), Amador (pop. 37,953), and Calaveras (pop. 45,052) counties. The lower end of the upper watershed begins at Pardee Reservoir (approximately 600 feet of elevation) and continues upstream to the headwaters in the upper Sierra at over 10,000 feet of elevation (Figure 1.1). It is upstream of the Lower Consumes-Lower Mokelumne watershed, which includes parts of Amador, Calaveras, Sacramento and San Joaquin counties (US EPA 2012, US Census 2010). The upper Mokelumne watershed overlaps with two National Forests—Eldorado and Stanislaus, with BLM as another primary Federal landowner in the watershed.

There are notable recreational uses on the river, including famous rafting and kayaking runs. The average acre of Eldorado National Forest receives about 56 inches of precipitation annually and average annual runoff is about 29 inches. This is roughly equal to 2.4 acre-feet of water per acre of land, per year (USFS 2013).

1.4 Fire History

The California Department of Forestry and First Protection, Fire Resource Assessment Program (FRAP), publishes data for California describing the areas in the state that are at risk from wildfire (CAL FIRE 2012). Significant portions of Amador and Calaveras counties are considered to be high or very high fire-hazard areas (Figure 1.2).

There are several communities in Amador, Calaveras, and Alpine counties that are at risk from fires from forested lands. FRAP forecasts significant future urban development in high fire hazard areas in the Mokelumne watershed, including central Calaveras County.

Figure 1.1: Map of Mokelumne River watershed

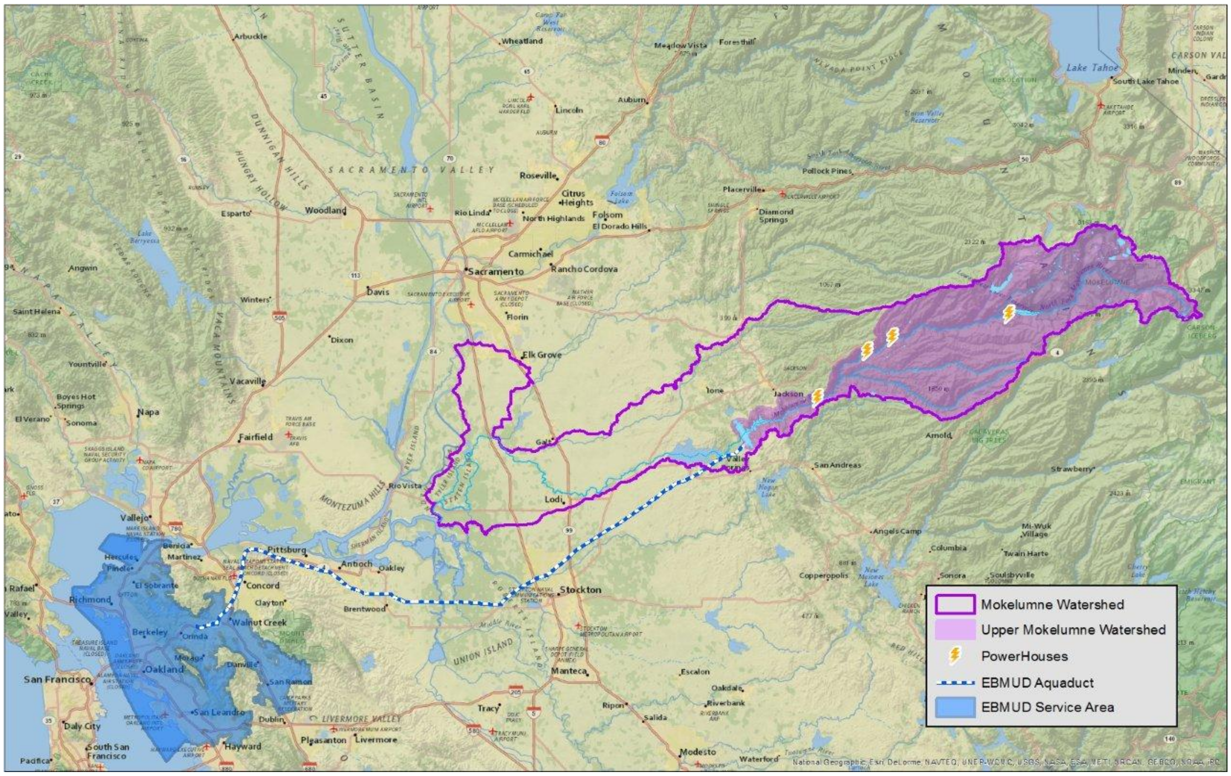
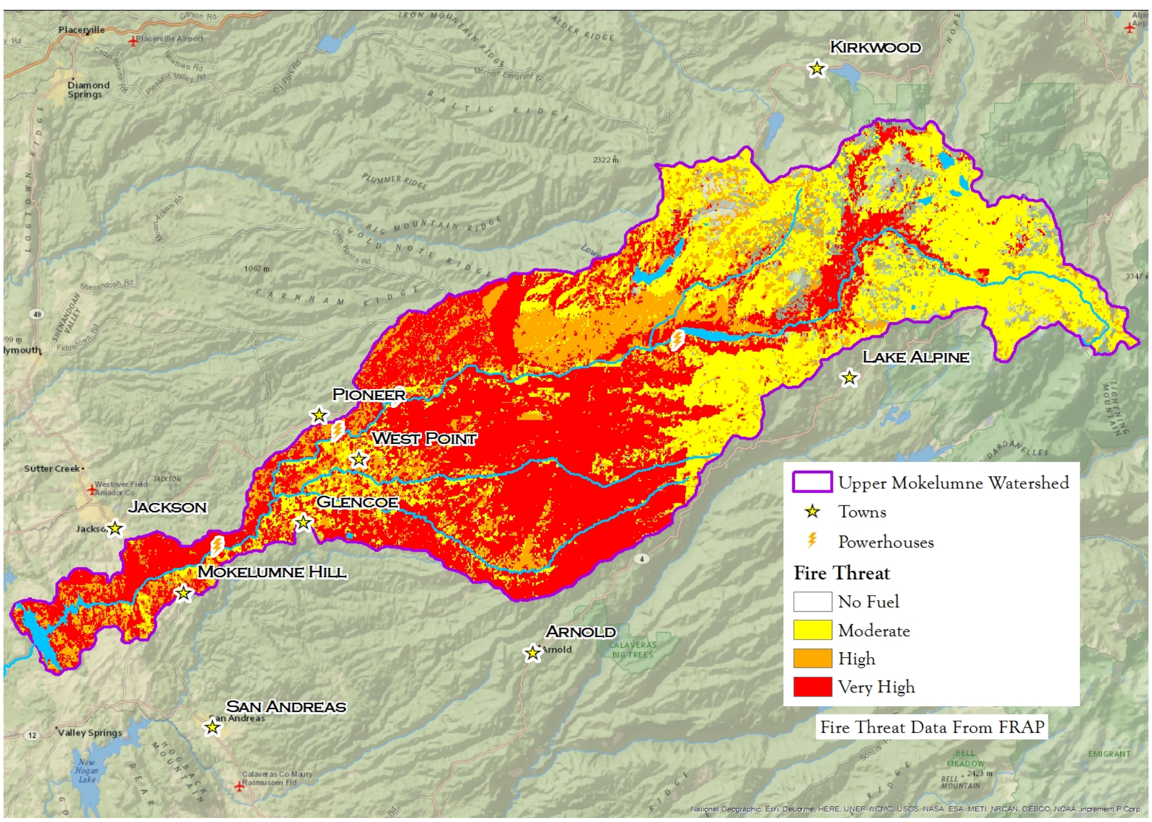


Figure 1.2: Map of fire hazard in the upper Mokelumne watershed



Wildfire in the Western United States is increasing in frequency, severity, and extent—both on the landscape and the calendar (Westerling 2006; Ecological Restoration Institute 2013). Lloyd's of London, one of the top international insurance agencies, issued a review of wildfire risk for insurers and concluded that climate change has increased the risk, and will continue to increase risk, of wildfire in western North America (Doerr 2013). In Chapter 3 and Appendix A we discuss the risk of wildfire in the Mokelumne watershed, based on the historic fire record for the area. However, as the 2013 Rim Fire demonstrates, the historic fire record may not be an indicator of future fire activity in the Sierra Nevada. If future fires in the Mokelumne watershed are more extreme than those modeled in this exercise, the costs would be expected to be higher than those discussed in this analysis.

1.5 Infrastructure

The East Bay Municipal Utility District (EBMUD) supplies much of the San Francisco East Bay's water demand, with 1.3 million customers. Over 90% of EBMUD's water supply, roughly 155 million gallons per day, comes from Pardee Reservoir (Figure 1.1) (East Bay Municipal Utility District).

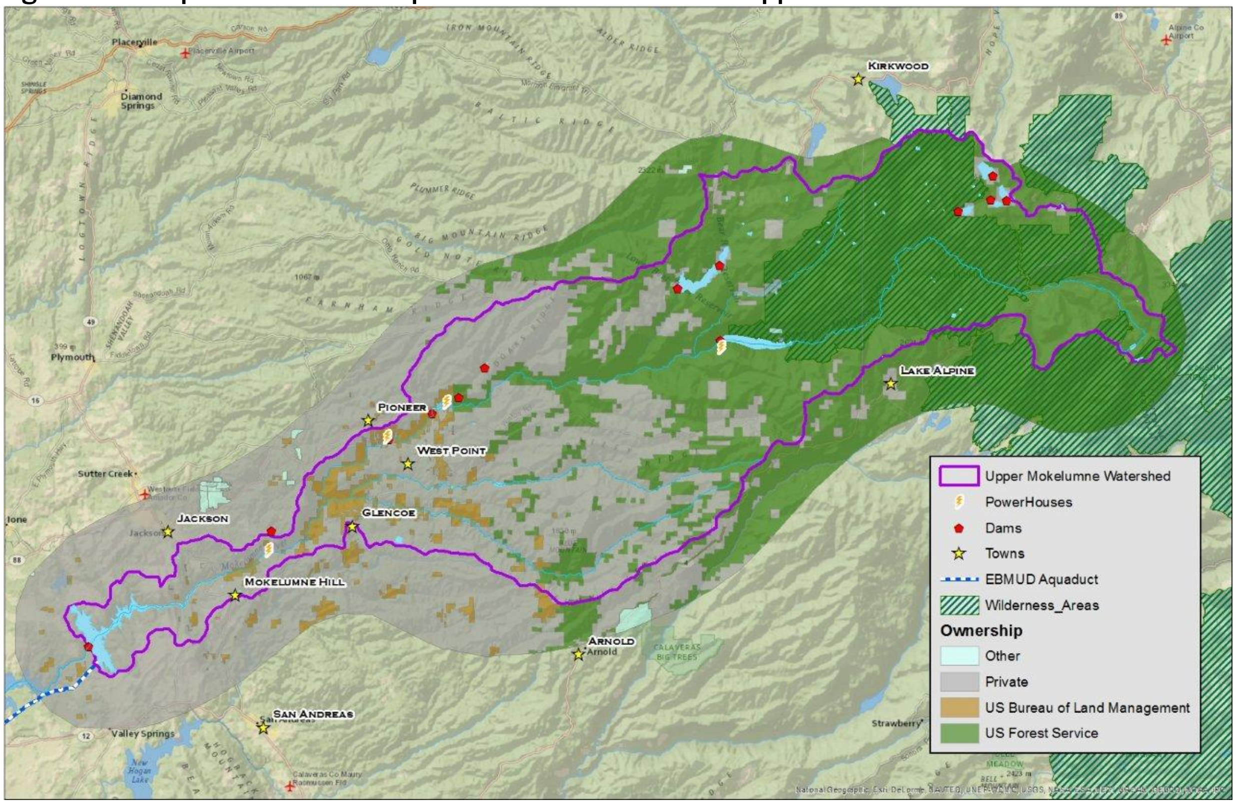
Pacific Gas and Electric (PG&E) operates a series of reservoirs, canals, and diversions in the upper Mokelumne watershed, with the majority of their reservoir storage located in Salt Springs Reservoir and all of their electricity generation situated downstream of Salt Springs Reservoir. See Chapter 6 for more information on utility infrastructure operations in the upper Mokelumne watershed.

USFS, BLM, the counties, the state, the utilities, and private landowners, including Sierra Pacific Industries, own and manage roads, transmission lines, and other infrastructure in the upper Mokelumne watershed (Figure 1.3). The area also holds rural homes and other structures at risk from wildfire, as well as timber resources, which are further described in Chapter 5.

1.6 Summary

This report documents an analysis of how upper watershed restoration treatments, in the form of fuel hazard reduction and forest health management, could benefit downstream beneficiaries. This includes the protection of property, structures, roads, and timber, as well as a reduction in the operational costs of energy and water delivery and the reduction in fire suppression and postfire restoration costs by state and federal agencies. The report also describes how these treatments can benefit socioeconomic and environmental conditions for watershed inhabitants and local resources.

Figure 1.3: Map of land ownership and infrastructure in the upper Mokelumne watershed



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Chapter 2: Process of Analysis and Scenario Development

2.1 Cultural Resource Values

Lands within the Mokelumne watershed contain an extensive record of human activity, with the heaviest use occurring within the last 4,000 years. Materials from the surrounding forest indicate that people have been visiting the general vicinity for at least 7,000 years. This area is very important to the local Native American communities and to the study of California culture and history.

By 5,000 years ago, permanent villages were well established on the western Sierra slopes at elevations generally below 3,500 feet. Two different Native American ethnographic groups (Northern Sierra Miwok and Washoe) were using the resources and residing within these lands by late prehistoric times. Archaeological evidence confirms rather heavy use within the vicinity. The site density and composition within the area is unique within the Sierra Nevada. Recorded Native American archaeological sites include a massive salt-processing site, ethnographic village and mourning (cry) sites, rock shelters, midden sites with house pits, petroglyph sites, and small food-processing sites. These sites range from 5 square meters to well over 20 acres in size. The North Fork Mokelumne was an important trade route between the Northern Sierra Miwok on the Sierra's western slope and the Great Basin tribes on the Sierra's eastern slope.

As a result, 15,398 acres along the north side of the Mokelumne River canyon were designated as the Mokelumne River Canyon Archaeological District and were determined eligible for inclusion in the National Register of Historic Places in 1992.

While cultural and historic values are exceptionally high within the Mokelumne watershed, it is impossible to place a monetary value on them. These values are irreplaceable should they be lost.

2.2 Process of the Analysis

Multiple meetings were held throughout the watershed to gauge interest in an ecosystem services project with a primary focus on evaluating the upper watershed forests' relationship with and economic values for downstream beneficiaries. After positive feedback from those attending meetings within the watershed, similar meetings were held with the primary utilities that manage hydropower and water in the watershed. The utilities expressed interest in whether or not a business case could be made that upper watershed conditions and management affect the utilities' operations, maintenance, and overall costs. This would be achieved through a robust scientific analysis of the risk of fire in the watershed, the consequences of fires, and whether strategically placed fuel treatments are a cost-effective means of reducing fire risk and consequences.

2.2.1 February 2012 – Advisory Committee

On February 1, 2012, the Mokelumne Watershed Avoided Cost Analysis Kick-off Meeting was held in Sacramento, CA. The Advisory Committee included representatives from the Sierra Nevada Conservancy, The Nature Conservancy, the U.S. Forest Service (USFS) (Region and District offices), the Bureau of Land Management (BLM), Sustainable Conservation, Pacific Gas and Electric (PG&E), the East Bay Municipal Utility District (EBMUD), and the Environmental Defense Fund. At the kick-off meeting, each organization presented its challenges and priorities for the watershed, and the stark contrasts between the challenges of land management at different elevations within the watershed quickly became apparent. Between the elevations of 1,000 and 3,000 feet, BLM manages relatively small parcels that are interspersed with private lands, and are frequently near homes or structures. Above 4,000 feet, where most of the USFS land is located, the parcels are much larger in size and the density of homes and structures is much lower. These differences require distinct management strategies. The kick-off discussion also focused on expanding the committee to include representatives from local government, conservation groups, tribes, and local private industry.

This meeting established the two overarching phases for the process: 1) the data collection, risk/consequence modeling, environmental and economic analysis, and a technical report; and 2) an implementation phase that could involve developing memorandums of understanding and funding arrangements. This report is the primary outcome of the first phase.

2.2.2 March 2012 – Advisory Committee

A meeting held in March 2012 set the stage for much of our subsequent work. The expanded Advisory Committee (which by then included representatives from Foothill Conservancy, Sierra Forest Legacy, Calaveras County, Sierra Pacific Industries, and the Amador Calaveras Consensus Group) developed the following analytical foci for the project:

- Fire suppression costs
- Postfire rehabilitation costs
- Costs to communities
- Costs to timber production
- Costs to wildlife
- Water-related costs, including water quality and supply
- Power supply-related costs, including supply disruption and maintenance
- Fire risk
- Biomass
- Carbon stocks

We also identified new potential project values:

- Improved upstream-downstream relationships and new partnerships
- Local involvement and perspective
- Creative ways to pay for restoration
- Transfer of the approach to the upcoming Forest Plan revisions

- Informing long-term planning
- Expanding investment
- Integrating disparate knowledge to understand a more complete picture of consequences to resource disturbances
- Identification of the beneficiaries of fire protection
- Risk mitigation
- Building a collaborative framework, including beneficiaries
- Better understanding of the water quality aspects affected by fire

The Advisory Committee began working on the project's charter, and each organization identified personnel from their organizations to participate in the Technical Committee. The Technical Committee would be the group of individuals that would determine how best to achieve the scientific goals outlined by the Advisory Committee.

2.2.3 May 2012 – Technical Committee

The Technical Committee convened for the first time on May 29, 2012, with a focus on identifying data needs and modeling options. In addition to the initial consideration of fire and sediment modeling, the possibility of including bark beetle and tree disease forecasts in the modeling process was discussed. Because of the direct connection between bark beetle tree kills and fire hazard, we decided to incorporate a bark beetle analysis into the methodology, to be undertaken by the U.S. Forest Service Forest Health Group. The suite of models to be used for the analysis is designed to be iterative, whereby the bark beetle model outputs are inputs for the fire model, and the fire model outputs are then inputs for the sediment model (Figure 2.2). We were faced with the important question of how to model sediment and which model to use. The sediment model selected for this analysis would need to meet several criteria: it should be able to crosswalk to the fire model (i.e., outputs from one can easily be used as inputs to the other), have good standing within the scientific community, and have outputs that are meaningful to the analysis. Each of our partner organizations looked internally to determine if their colleagues could recommend a sediment model that they were familiar with or had used in the past.

We also discussed the importance of tracking and reporting information about assumptions and decisions, and The Nature Conservancy took the lead on composing an assumptions document (Appendix J). Other important questions that were raised included the geographic boundary for the analysis and what the baseline for vegetation would be. The primary basis for this question was whether or not to include fuels-related projects that are pending within the watershed. Put another way, if projects resulting from this analysis were not likely to be implemented until 2015, would it be worthwhile to account for any projects that may occur during that time that may affect fire behavior within the project area? [*In the end, we decided to not include upcoming projects primarily because these projects could change based on the outcomes of this modeling process. Additionally, the benefits of adjusting the vegetation layers to predict the projects' outcomes would not outweigh the benefits.*] We began to consider the factors that may drive the need for different modeling scenarios, including future management plans and climate change. The decision was made to first review the results of the baseline model run and use this information to develop the scenarios.

2.2.4 June 2012 – Advisory Committee

The June 2012 meeting focused largely on the modeling process. For most treatments, we decided that the methods described in the USFS General Technical Report (GTR) 220 would be the basis for our design. We also discussed the role of chronic sediment sources on the sediment budget, such as poorly constructed and managed roads. As opposed to sediment postfire, sediment from roads can be a constant sediment source within the watershed. Despite the magnitude and importance of chronic or annual sources, this type of sediment source falls outside the purview of this analysis and thus was not included in this phase. Instead, it is assumed that any erosive event that occurs due to a fire is additive to the sediment load produced by chronic sources.

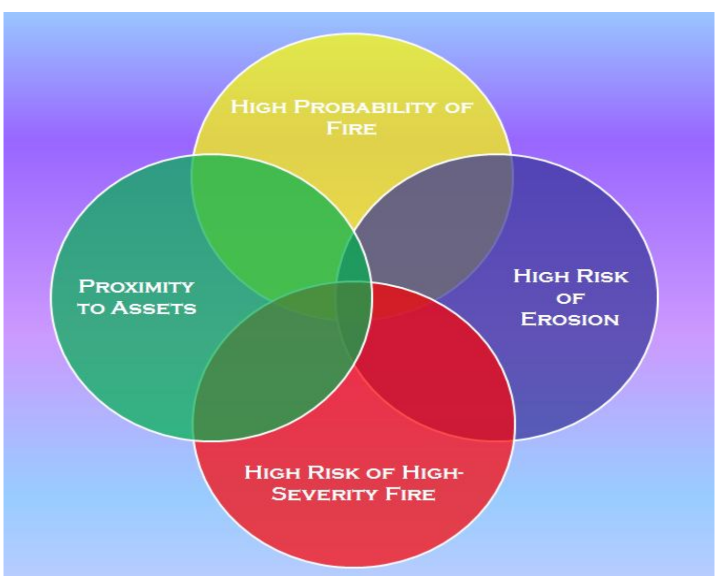
We then began developing a list of model scenarios to consider for the analysis:

a. *Baseline* – Current forest conditions and expected sediment when a fire occurs
b. *Cornerstone* – The changes that the Cornerstone Project (watershed Collaborative Forest Landscape Restoration Act project) will have on baseline conditions
c. *High-Priority Areas* – Use the baseline scenario results to define high priority areas in proximity to electric and water assets at risk and re-run the model with fuel treatments in these locations and compare results to the baseline scenario
d. *Climate Change* –A sub-scenario of each of the preceding scenarios to show how climate change influences each scenario

The locations where three or four criteria overlapped were identified as the high priority areas (Figure 2.1):

a. High probability of fire
b. High probability of high severity fire if a fire occurred
c. Proximity to assets/infrastructure (direct fire damage)
d. High risk of erosion impacts (indirect fire damage by way of sediment delivery)

Figure 2.1: Overlap of criteria to determine high priority areas



We also reaffirmed that the modeling effort would be a sequential and iterative process (Figure 2.2).

Figure 2.2: The sequential order of the modeling process

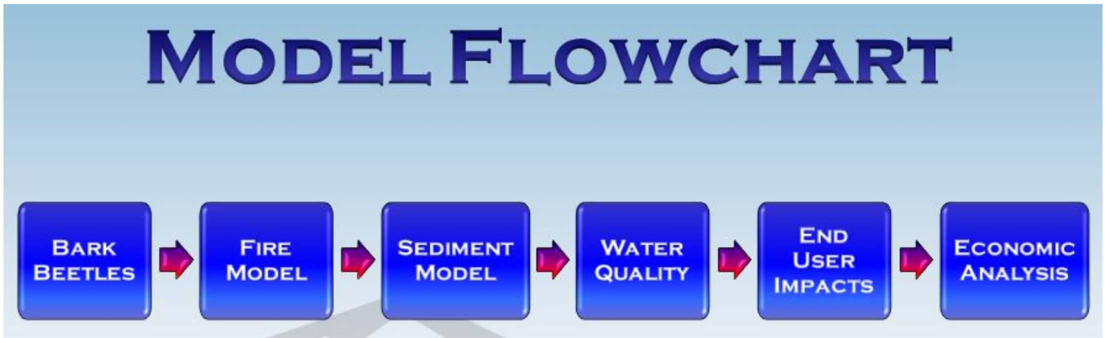


Figure 2.3: How economic analysis would lead to the identification of investors

For the remainder of the June 2012 meeting, we turned our attention to defining the term “investor,” as well as which investors could potentially benefit from the findings of this analysis. A flowchart for the analysis was proposed, as shown in Figure 2.3. We would identify valuable services that are relied upon by businesses and then determine if we would be able to calculate impacts to those businesses through this analysis. Pending the results of the analysis, the investors in those businesses could then be approached with a business case relative to their concerns. Our brainstorming session led to the following potential list of investors to support forest treatments and fuels reduction:

- Utilities
- Local government (and communities)
- Tribal governments
- Private landowners
- Federal and State agencies, (e.g. public health agencies, Cal EPA [for the purpose of greenhouse gas emission reductions], and CA Corrections [seeking an outlet for its prison labor force])
- Environmental organizations
- Recreational organizations
- Private foundations (including corporate philanthropy)
- Green and/or local businesses (including future beneficiaries of a diversified forest economy, e.g., small woody biomass use)
- Insurers

    - Public Health (e.g. Sutter Health, California Healthcare West, Kaiser Permanente, CalPERS)
    - Property/Home
- Local water purveyors
- US Army Corps of Engineers

Based upon the list of potential investors and the assets in the watershed, we developed the following recommendations for potential costs to analyze:

- Fire-related costs
    - Fire suppression
    - Postfire restoration
    - Timber production on public lands
    - Timber production in areas where private and public lands meet
- Water quality treatment and supply costs
    - Sediment loading
- Power supply and infrastructure costs
    - Sediment loading
- Community and public safety costs
    - Homes and vegetation in the wildland-urban interface (WUI)
    - Rural community infrastructure (e.g., telephone lines, water and sewer lines, mobile communication facilities, roads)
    - Rural residents' values and perceptions (security, safety, aesthetic enjoyment)
- Costs of impacts to fish and wildlife
    - Salmon fishery
    - Sensitive species habitat (e.g. CA Wildlife Habitat Relationships)
    - Culturally significant plant species
- Costs of impacts to urban sector (e.g. recreationalists, camping, rafting, hiking, birding)

2.2.5 Modeling Observations – Summer and Fall, 2012

A key component to improving the reliability of the modeling process was to have the modeling teams tour the watershed with local experts and Committee members. These field trips occurred for the fire modeling team in June 2012, and for the sediment modeling team in November 2012. In both cases, the resulting model runs were considerably more robust as the modelers were able to adjust the "stock" parameters of the models to the site-specific conditions they observed (see the appendices for more information on the models).

The modeling teams' field visits helped them adjust the base layers (e.g. LANDFIRE vegetation layer), the inputs used in the model, and the model parameters to better reflect on-the-ground conditions. For example, the fire modeling team visited high-risk areas with a local fire chief (a member of the Technical Committee) and viewed regeneration of an area that burned at high intensity almost a decade ago. This visit helped them revise the model inputs and parameters so the model would more accurately model fire on that area. The fire modelers updated the baseline vegetation data at the lower elevations by adding more grassy areas and at higher elevations by adding more rock. They also significantly altered the ignition model parameter for the fire model and broke it into three elevation bands to ensure that ignition patterns would be appropriate based on many factors, including the duration of the snowpack into the spring and summer. The site visit helped the sediment modeling team adjust the soil profile for a variety of watershed locations and the soil coverage in postfuel treatment sites.

2.2.6 September 2012 – Technical Committee

The difficulty of developing a complete picture of sedimentation through models became apparent during the September 2012 meeting, but the decision was made to move forward with a fine sediment (2mm in size and less) hillslope erosion model using GeoWEPP (Appendix C). This model does not account for sediment sourced and transported by roadways, gully formations, landslides, and within water channels. [*This discussion continued for several months as options were considered in an attempt to reliably track as many sediment sources as possible. The result was the selection of three different sediment models as the best means to develop a general picture of non-chronic sediment transport and erosion pre- and postfire: GeoWEPP (fine sediment), FERGI (gully formation), and a landslide regression mode (debris flow). A channel sediment transport model was sought, but the appropriate model for our needs was not found. The WARMF model, which had been used and calibrated to the watershed previously by EBMUD, was intended to be used to model water quality parameters in the waterways as a result of fire, but the appropriate crosswalk between it and the fire model was not found.*]

This meeting provided time for the modeling teams to discuss the inputs, running procedures, outputs, and timeline. At this point, there were four distinct modeling teams participating: GeoWEPP, FERGI, tree insects and diseases, and fire. Through discussion, the modeling teams were able to find efficiencies and reliability through shared datasets. As each modeling team discussed their needs and potential hurdles, it allowed for clarifications of potential incompatibilities across the modeling efforts, such as the differing biophysical breaks (i.e., elevation bands the models break terrain into) that the fire and GeoWEPP models use. Each issue was tackled as a group, with consensus guiding the solution. For example, in the case of the elevation bands, we decided that the difference in elevation breaks between the two models was small enough that it would be more important to run the models within their optimum parameters than to align the breaks and potentially affect the accuracy of the results. The modelers were able to discuss their timelines and when their outputs would be available to others, allowing each team to better predict their own timelines. The skill set of the Technical Committee allowed the modeling teams the opportunity to vet their approach with other experts in their field as well as with local experts, once more improving the reliability of the results.

2.2.7 October 2012 – Advisory Committee

A primary goal of the October 2012 meeting was to expand the circle, from both the public-relations standpoint and the focus of the analysis. News of the analysis had been spreading throughout the region and the need was identified to share information with regional groups. Members of the Advisory Committee volunteered to reach out to these groups and to present materials from the analysis, receive feedback, and to determine how to coordinate efforts that overlap. Aiding this endeavor, the charter for the analysis was agreed upon during this meeting, defining the roles and responsibilities of the partners.

Committee members expressed interest in expanding the scope of the analysis and provided a list of areas to include. A ranking exercise was used to prioritize areas that could be added to the analysis, either quantitatively or qualitatively. The options were presented to the group by the Project Manager consulting team, which had identified ecosystem services that were likely to attract investment to the watershed and that were appropriate to the analysis based on their compatibility with the modeling effort and the available data. The top five priorities the committee identified were:

- Water quantity and timing
- Forest products (e.g., local biomass use)
- Tourism and recreation
- Carbon sequestration
- Clean air and water quality

The ecosystem services that would not be part of the analysis were:

- Wildlife and wildlife habitat
- Fisheries and fish habitat
- Cultural resources

A primary reason why these three were not considered for this analysis was that they were being addressed through other projects in the watershed. Also, in some cases, the group could not gain access to the data necessary to evaluate them appropriately.

The Committee also discussed how priority areas would be framed and how to define scenarios for the modeling effort beyond the baseline condition. Priority areas would be primarily determined by the results of the baseline model runs for fire and sediment, as well as the following:

- Project plans from other efforts within the watershed, especially the work being planned as part of the Cornerstone Project
- Threshold size
- Timeline
- Vegetation regrowth
- Cost effectiveness

For any given scenario, the following timescale considerations were highlighted:

- Would the treatments be modeled as if they occurred within a single year?
- What is the threshold for minimum effective size and timescale?
- Would the scenarios factor in regrowth and treatment maintenance?

The following sections of this chapter provide more information about how the priority areas were identified and the treatment conditions developed.

2.2.8 November 2012 – Technical Committee

A discussion of modeling efforts dominated the November 2012 meeting, given the fact that there was no reliable way to link the bark beetle model to the fire model. Because of this, the fire model results would not be influenced by the results of the insect and disease analysis. One can infer that the forest stands highlighted in the insect and disease analysis are susceptible to attack and are therefore at greater risk to fire than the fire model results indicate, but no quantitative values are associated with such an inference. For more information on the insect and diseases results, please see Appendix B.

The fire model was run at a scale considerably larger than the upper Mokelumne watershed to help identify areas outside of the watershed where fires could start and then move into the watershed. Prior to this meeting, the trial run had identified the areas outside the watershed where fuel treatments could be effective at reducing the probability of fire that could move into the watershed. As the group reviewed the model results from the trial runs, our discussion centered on the rate of spread and the fire size limitations in the trial runs. We determined that the model results had more than enough accuracy to achieve one of the goals of the analysis—to identify fire behavior differences under current forest conditions compared to treated areas.

2.2.9 December 2012 – Advisory Committee

With the work plan for the consulting team set during the October meeting, the goal for the December meeting was to determine ways to expand upon the final product to add more value. This was due in part to the fact that secondary targets—those which the consultants would not quantify, such as tourism and recreation—can increase the potential investor pool, adding value and potential support. Three ways to potentially include the secondary targets in the final analysis in at least a qualitative fashion were:

1. Taking into account previous work done in the watershed
2. Literature reviews
3. Partnerships

The Mokelumne watershed has been the focus of a significant number of groups and projects over the years, many of which may be potential sources of local data and/or knowledge that would be inexpensive to access and incorporate. Similarly, literature reviews could uncover trends that may apply to the watershed without the need to perform costly and time-consuming analyses within the watershed itself. Lastly, analysis partners, especially local organizations with their rich knowledge of the watershed, could independently evaluate issues and report back to the Advisory Committee. These three sources of information were vital to the development of the work plan, and applying them to secondary targets could be an efficient way to evaluate the targets' potential avoided costs.

The consultants provided context on upcoming decision points we would face, with a focus on the treatment conditions to select. Key questions were: what areas of the forest should be treated, what practices should be used to treat, and at what scale should the treatments occur? The next sections of this chapter have more details on the development of the treatment scenario. To help with the upcoming decisions, the consultants designed a method to break the watershed into 148 discrete units. These units were small enough and specifically designed to capture similarities in areas with respect to fire, sediment, slope aspect, and drainage so that averaging across the unit would not dilute important information. At the same time, the units were large enough to allow participants in this process to more easily visualize the trends of the model results from a full watershed perspective. The units were referred to as Analysis Units (AUs) and were an average size of 2,500 acres (maximum: 12,500 acres; minimum: 217 acres); they are similar to the Planning Units that the USFS relies upon but are much larger than the typical USFS Treatment Unit.

One difficulty the group faced at this point was that the data gathering for multiple elements in the process was occurring at once. The best way to develop a decision process would have been to optimize treatments based on dollar values (e.g. asset values and treatment costs), since this analysis is focused on avoided costs. Such an approach would have allowed a focus on treatments in areas where the highest asset values intersect with the greatest fire and sediment risks. The consulting team was actively developing a complete picture of the assets in the watershed, but it would not be complete in time to be a factor in the decision process of selecting areas to include in the treatment scenario [*In the end, we used building-density data, along with a variety of infrastructure data layers, as a proxy for asset values in our decision making process]*. However, we flagged the following criteria as those that would help optimize treatments, if the data could be available in time:

- Fire hazard (fire risk and assets at risk)
- Risk to infrastructure and timber
- Population density
- Land ownership
- Cost of treatments and maintenance
- Sediment yield
- Urban and wilderness land use designations

2.2.10 January 2013 – Technical Committee

With most of the modeling for current conditions (baseline) complete at the time of the January 2013 meeting, the process began to shift toward the development of one or more scenarios to compare to the baseline condition results. The purpose would be to determine what impact, if any, fuel treatments could have on reducing the risks posed by wildfire. The assumption made was that fuel treatments can reduce fire threat, but the degree to which fire threat is reduced can vary depending on the types of treatments that are used and their placement across the landscape.

The Technical Committee was broken into three groups and each group was provided with six maps, each with a range of model and watershed information to help members determine where to place treatments within the watershed. The groups were provided a loose framework to guide their discussions, but their priorities were determined within the group. Each group developed a recommendation on which AUs to treat and presented their recommendation and reasoning to the rest of the Committee. Group 1 focused their hypothetical treatments in clusters around areas that, if a fire were to start there, would be hard to control. This included steep, inner canyon areas, especially those near the wildland-urban interface (WUI) or recreation areas. Group 2 also used a cluster approach and based their treatment selections on where building density (a WUI proxy) and high fire intensity overlapped. Group 3 focused on areas that would have a high flame length and where fire could spread or could lead to heavy sedimentation runoff. They also selected areas that had assets at risk for fire damage. More on the group selections can be found later in this chapter.

Based on the feedback from this initial exercise, including which maps were useful during the selection process and what missing data elements would have been helpful, an online map environment was created to facilitate the input that both Advisory and Technical Committee members would provide to the process. The results from the models, along with a number of physical datasets, including building density, roads, and utility infrastructure, were uploaded to Arcgis.com. Each Committee member (Technical and Advisory) was given access to the site and was asked to select the AUs that they believed should be in a treatment scenario. Individual selections in a mapping environment made compiling, analyzing, and displaying the results much more simple. The feedback from the participants following this exercise was overwhelmingly positive.

2.2.11 February 2013 – Advisory Committee

Outreach to regional groups by members of the Advisory Committee had begun by February 2013 and the need for outreach materials to support these efforts was identified. Two different target audiences for the materials were identified: potential investors and the general public. The group discussed developing a brochure that could potentially be part of an EBMUD mailing, as well as creating a website for the project.

2.2.12 April 2013 – Advisory Committee

The Advisory Committee vetted the results of the Treatment Team selections (see below) in the April 2013 meeting. It was decided at this time that the canopy code for the riparian treatments needed to be changed from moderate to low, indicating that the canopy within riparian areas would be essentially undisturbed within the treatment scenario. A similar change for the treatment approach to steeply sloped areas was also recommended and accepted.

An in-depth discussion of how each land manager on the Advisory Committee approaches treatments on their lands followed, which highlighted the contrasting styles and restrictions the managers have in implementing treatments. In the lower elevations, the land is heavily fragmented, with public lands dispersed between multiple homesteads. Because of the fragmentation, management options are limited (e.g., prescribed fire is rarely used) and treatment costs are much higher because the high cost of staging for treatments is incurred for relatively small treatment areas. The land managers also shared that they often work with other public and private organizations in the area, including Fire Safe Councils, to achieve their goals. In the higher elevations of the watershed, the land managers have more management options and treatments in general are cheaper per acre because the lands are less broken up in ownership. However, competing priorities, such as degraded roads and meadows, often vie for the same pot of project money.

2.2.13 May 2013 – Advisory Committee

The fire model team reported the results of the treatment scenario during the May 2013 meeting. In general, the treatments were very effective at reducing both flame length and fire risk. But there were a couple of unanticipated issues, the greatest of which was the response of grassy areas to treatments. Because the model parameters were overlaid on a diverse set of vegetation types, it was likely that some of those would not respond well to treatments designed for forests. As a result, the treatment scenario allowed for much more grassland regrowth than would occur under normal circumstances; the model reflects this with increased flame length, rate of spread, and burn probability for those areas. The lesson we learned is to remove vegetation types from the treatment scenario that the intended treatment would never be prescribed to.

With the treatment scenario defined and results beginning to take shape, we used GIS data from partner organizations to compare upcoming planned and proposed projects with the treatment scenario. In some places, proposed projects overlapped with areas the model results suggested would be very effective. The land managers in the Advisory Committee were unanimous in their declaration that they will be looking to these data and the results to help refine their upcoming projects. Where the goals of those projects overlap with the results of this analysis, that information will be used to maximize the benefits. One result from having these representatives in the same room and reviewing the data together is the potential for the agencies to coordinate efforts across land ownership boundaries to achieve the greatest impacts in the most efficient way possible.

As the structure for the final report for the project began to take shape, we discussed at length the audiences it should speak to. We determined that the executive summary should speak to a broad range of audiences from diverse backgrounds, and the summary should distill the results of the study into concepts that are easily understood and relatable to the general public. Likewise, the report should, at least in sections, speak to ratepayers for utilities potentially impacted by the results, as well as to the actuarial scientists that manage the risk management divisions of organizations with assets in the watershed.

2.2.14 June 2013 – Technical Committee

With three different sediment models incorporated into the analysis, the Technical Committee discussed how to integrate the results of the three models into one reporting method. The challenge stemmed from the fact that each model used different weather events to obtain its results, and reported those results in different units. For example, the GeoWEPP model outputs are the result of averaging multiple years of weather patterns, whereas the Debris Flow model uses specific rainfall intensities to create its outputs.

This discussion overlapped with the issue of burn probabilities and how reliable it would be to use historical data in the fire models to predict future behavior, when recent trends indicate that fire seasons over the last decade are more destructive than ever before. At the same time, what reasonable assumptions can be made about fire probabilities over the next few decades if they are not based on the past? The group decided that we would frame the conversation similar to a discussion about 5.0 and 7.0 earthquakes: describe an average fire event within the watershed as well as a less probable but more destructive event. Using the fire model outputs, we teased out five discrete fire boundaries and identified fires that correspond to both average events and less probable but more destructive events. By using the fire perimeter and burn intensities, we plugged in specific postfire weather patterns and created predictions based on the other modeling work of the damage those fires could cause, both from direct fire damage and from postfire sediment runoff. This provided perspective on both likely and less likely events and provided tangible results that can be better understood by the general public than if we had used burn probabilities.

2.3 Stakeholder Selection of Forest Treatments to Reduce Fire and Postfire Sediment

The focus of this study is an assessment of the environmental and economic costs and impacts of the current watershed condition compared to a future modeled management scenario. This chapter describes the process we followed to develop the modeled management—or treatment—scenario.

Following the first round of fire and postfire sediment modeling based upon existing conditions, the Technical Committee, with input from the Advisory Committee, needed to determine the extent, location, and type of hypothetical forest treatments that could reduce fire and postfire sediment risk. (The rest of this chapter provides more details on how the team selected the treatment types.) The resulting treatment selection became the basis for the modified vegetation layer used in the second round of fire and sediment modeling. The committees made their treatment selection with incomplete information regarding the distribution of assets and cost of treatment.

Information on the locations of hydropower facilities and water intakes were available, but we had not acquired specific data on additional infrastructure throughout the watershed that was at risk to wildfire. This includes the location of many valuable resources, including cultural heritage sites, wildlife habitat (except Protected Activity Centers), or Wild and Scenic River designated areas, all of which would affect the potential implementation of the modeled treatments. A collaborative process with input from stakeholders living inside the watershed and land managers familiar with the watershed's assets helped bridge this gap. The diverse stakeholder input added a range of important qualitative values to a largely scientific modeling effort. With only one opportunity to run a modeled treatment scenario in the fire and sediment models, stakeholders took a fresh view of the entire watershed upstream of Pardee Reservoir and used the fire and postfire sediment model data to inform their treatment selection.

The purpose of the treatment selection process was to create a model scenario that would reduce wildfire and postfire sediment risks, with a focus on the water utility infrastructure. With the hypothesis that wildfire and postfire sediment would negatively affect utilities dependant on Mokelumne River water by direct fire damage, through filling of reservoirs with sediment, or decreased water quality from suspended sediment in postfire flows. Prior discussions with Pacific Gas and Electric (PG&E) informed the committees that sediment does not affect their hydropower operations in the Mokelumne watershed largely due to two reasons. They are able to flush sediment from the water intakes at key reservoirs (e.g., Tiger Creek Afterbay), and much of their water conveyance infrastructure consists of off-stream pipes or canals that allow PG&E to choose from multiple sources and easily clean out conveyance infrastructure. From the perspective of the East Bay Municipal Utility District (EBMUD) and their operations, upstream hydropower reservoirs act to trap sediment and prevent it from reaching Pardee Reservoir. River sections between Pardee Reservoir and the hydropower dams, as well as the Middle and South Fork Mokelumne, could affect Pardee Reservoir where EBMUD has their water intake.

Selecting forest treatment areas using a collaborative process versus model results—which would have led to the selection of treatment areas based on fire and sediment risk—captured a larger portion of the watershed for treatment, including the wildland urban interface (WUI) and areas with infrastructure at risk to direct fire damage. Comparing the final stakeholder-selected treatment area that falls within the United States Forest Service (USFS) boundary to existing USFS planned treatment areas illustrated the utility of the advanced fire modeling made available in this study. It is important to note, however, that local land managers have their own specific management goals that may take a higher priority over the issues captured in this analysis; their projects are designed to meet multiple objectives and account for many factors, including sedimentation.

In addition to providing an avoided cost analysis of proactive forest management, this study can help inform the Amador Calaveras Consensus Group (ACCG – a local stakeholder-driven collaborative process), Fire Safe Councils, USFS, and Bureau of Land Management (BLM)'s prioritization and location of treatments.

2.3.1 Methods

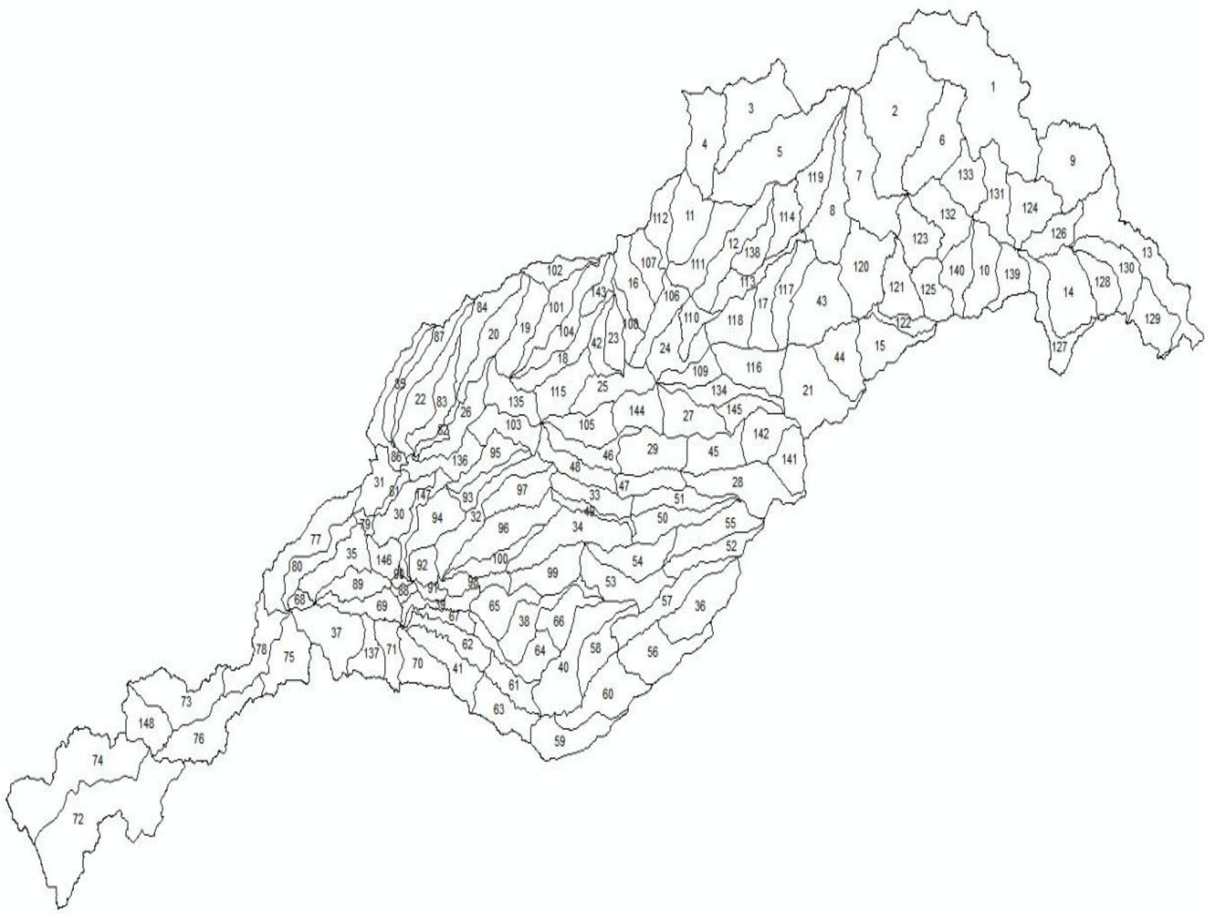
Stakeholders selected treatment areas across the entire watershed, including urban, BLM, USFS, and private land.[1] We excluded from treatment designated wilderness and roadless areas, despite the relatively high predicted insect mortality rates on some of those lands (Appendix B), per the USFS. These areas are located in the highest elevation portion of the watershed and have few management options or infrastructure. We summarized the pixel level data from the fire and sediment models into averages by subwatershed areas called Analysis Units (AUs). Each AU was approximately 2,500 acres in area and there were 148 total AUs within the watershed (Figure 2.4). Summarizing the pixel level data by AU made it easier to discuss the treatment selection and to identify the specific land areas that drained to specific reservoirs and water intakes. At the same time, the AUs were small enough and specifically designed to capture areas that had similar trends in the model results so that the upscaling from the pixel size (30 meters squared) modeling results to the larger AU size would not mask or dilute important results. In addition, we included areas outside of the watershed where fire could originate and spread into the watershed, which we refer to as Influence Units (IUs).

To determine the extent of treatment area necessary to reduce the fire risk, we first reviewed the literature. Overall, the literature suggested that fuel treatments on approximately 30% of the watershed reduce the overall fire risk (burn probability) for the whole watershed. The minimum area required to reduce fire risk from high severity fires moving across a landscape is 10-20% (Ager et al. 2007, Finney et al. 2007). As the area thinned increases beyond 20%, the rate of reduction in fire risk changes more gradually. Ager et al. (2013) modeled fire behavior and concluded that the strategic placement of treatments across 35% of the landscape were optimal to reduce wildfire

[1] Note that PG&E did not make a treatment selection.

mortality of old growth forests, compared to <20% or >80%. At the Sagehen Creek Experimental Forest, the ecological thinning planned for 2013 will treat 29% of the watershed (USDA 2011) to both reduce fire risk across the Experimental Forest and to improve its ecological function. Treatment rates of 1% to 30% per year had a maximum effectiveness of reducing fire risk for approximately two decades (Finney et al. 2007).

Figure 2.4: Analysis units (AUs) within the Mokelumne watershed—subwatershed areas that average 2,500 acres in size

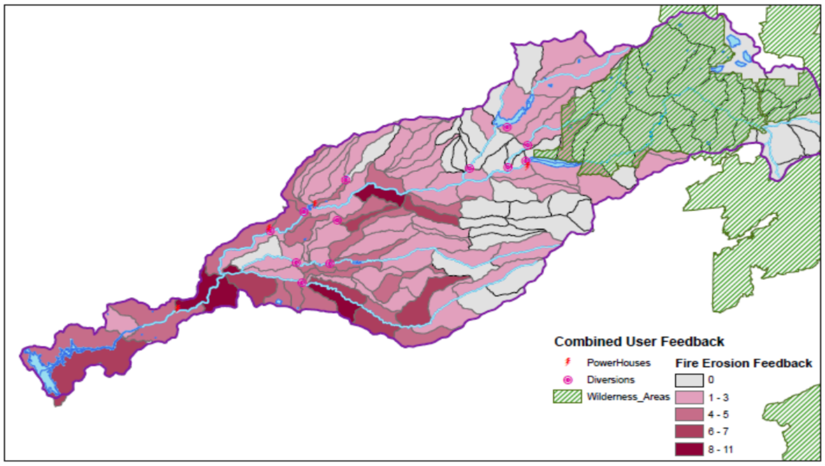


Selecting where to locate forest treatments was a collaborative process, with input provided in a group working session and then through an online ArcGIS platform. During the working session, three groups of 7-10 people discussed where to treat the forest based on the model results and their own expertise. We collected notes and their treatment selections and shared the information with the larger group before the online selection process began (see Group Working Session notes at the end of the chapter).

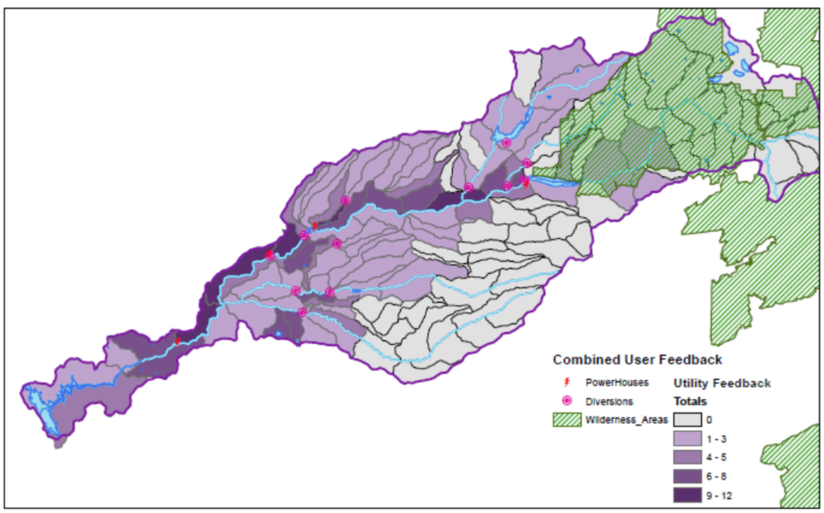
Stakeholders had two weeks to make online selections of treatment AUs using an ArcGIS platform (see Online GIS Participation Instructions at the end of the chapter). The online tool allowed each user to view all of the model results in a map viewer, in addition to many physical data sets such as building density, land ownership, and topography. This allowed the stakeholders to review and analyze all of the model data and many of the relevant decision factor data from different perspectives, including zooming and switching layers on and off. Individuals did not see each other's selections and each organization was able to have as many of their employees participate as they deemed reasonable. Users made selections to two maps: one with the mean fire and erosion results ranked into five quantile classes, and one with the utility burn probability ranked into five quantile classes. These maps contained additional layers that users could switch on or off, including water conveyances, wilderness and roadless areas, towns, hydropower powerhouses, electrical transmission lines, and municipal water intakes. During the selection process, users were asked to record the rationale for their selection of a particular AU.

After the stakeholders provided their input, we overlaid all of the stakeholder selections for both maps and determined the top selected AUs (Figure 2.5). A thorough discussion of these results with both committees further refined the priority areas. Coincidentally, by the time we included the additions that resulted from the meetings, the total area to be included in the modeled treatment scenario was approximately 30% of the watershed. To compare the stakeholder treatment selection to a selection based only on the fire and sediment model results, Phil Bowden, who performed the fire modeling for this analysis, calculated the top 40 AUs based on the highest risk (Figure 2.6).

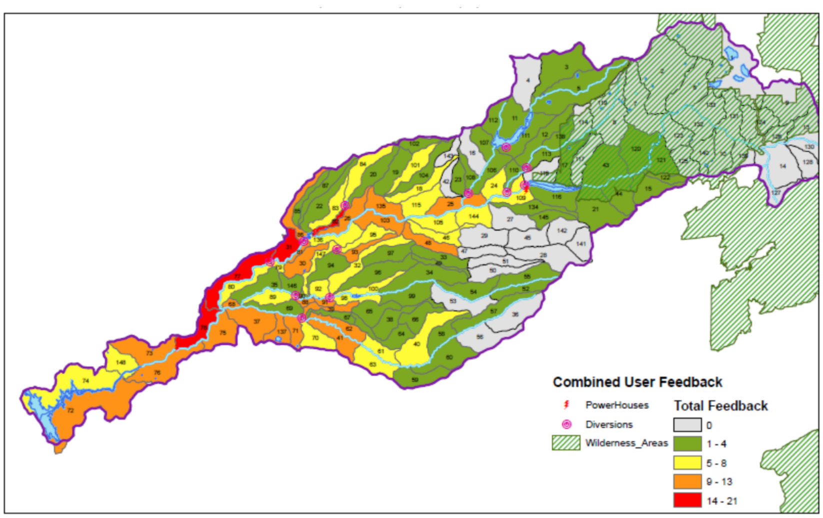
Figure 2.5: User selections for the mean fire and postfire erosion map (a), direct fire risk to water utility map (b), and combined user selections from maps a and b (c).



(a)

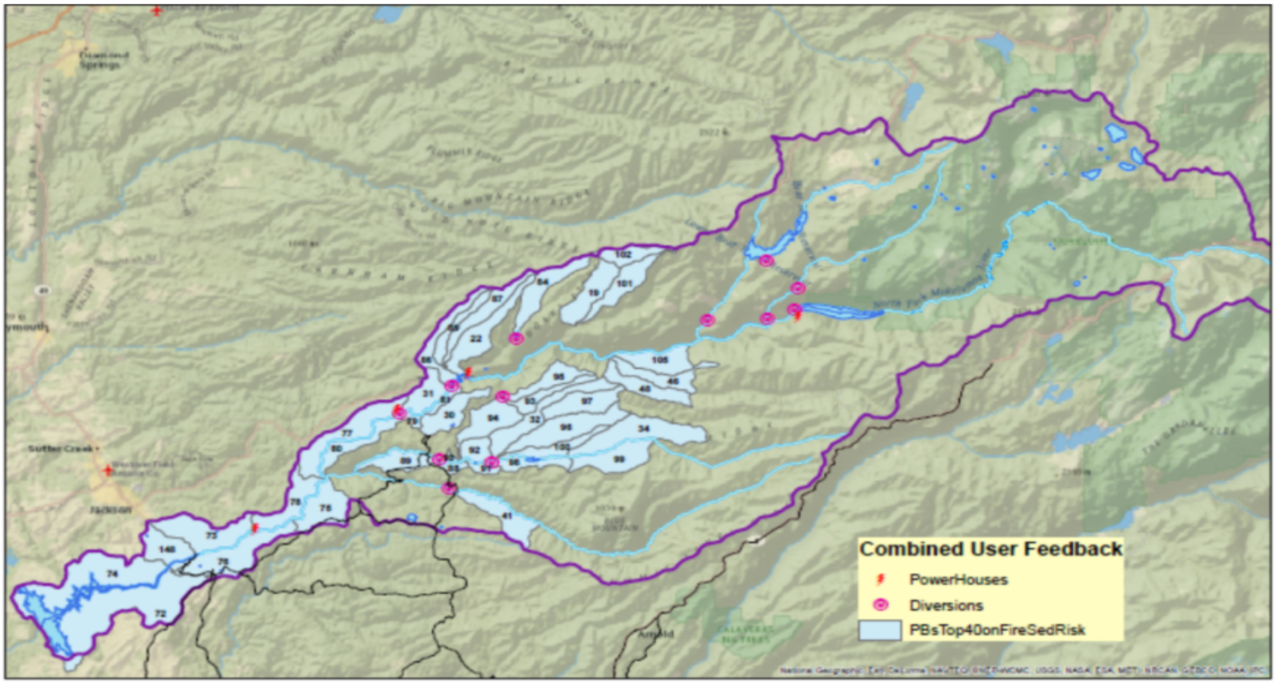


(b)



(c)

Figure 2.6: AU selection based only on fire and sediment risk model results - by Phil Bowden (USFS)



2.3.2 Results

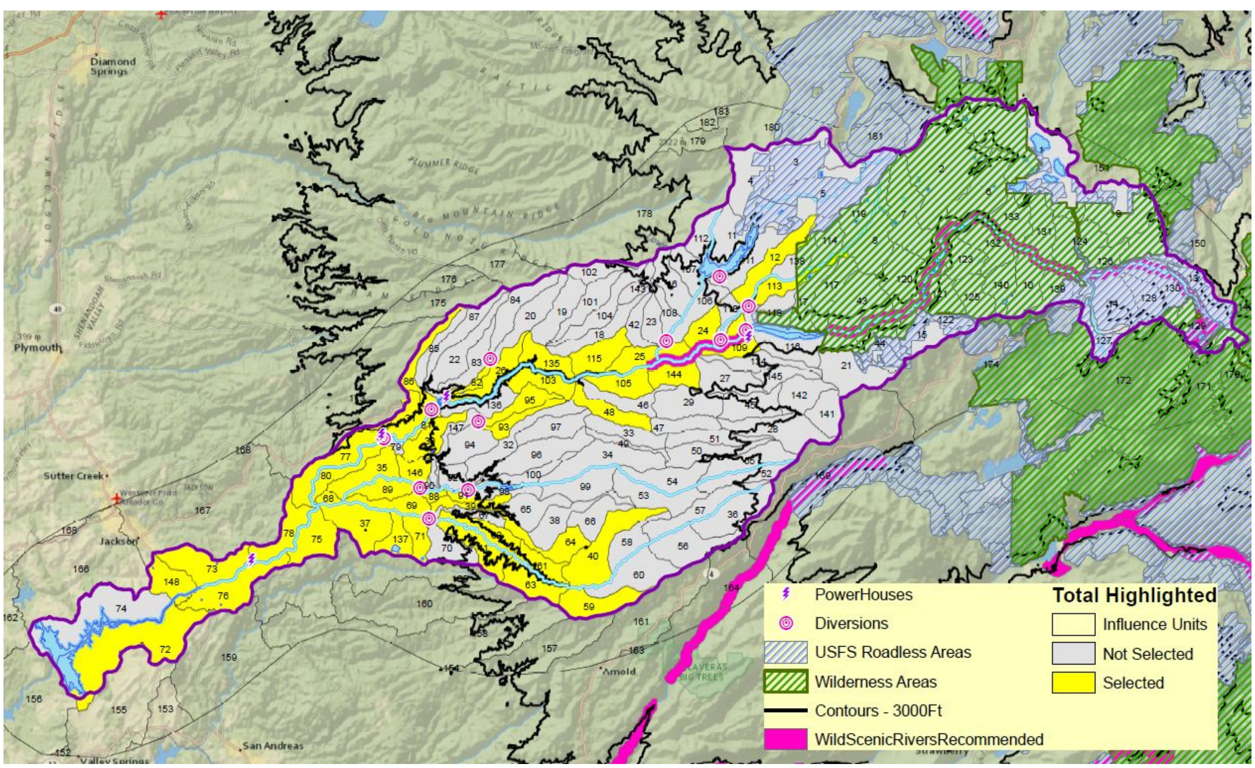
Through the iterative process of treatment selection, we decided to treat 46 AUs covering 99,894 acres, or roughly 29% of the watershed (Figure 2.7). All of the treatment areas were inside the watershed, even though the fire model showed a high probability that fires that start outside of the watershed could move into the watershed. Throughout the stakeholder selection process, the only bias we detected was between the inside- and outside-the-watershed stakeholders. Stakeholders outside the watershed selected AUs based more on the model results, whereas stakeholders inside the watershed relied more heavily on their local knowledge of assets and other factors. During the working group session, on the mean erosion and fire risk map, the groups identified clusters of AUs to treat based on a common objective as decided within each individual group. These objectives included recreational use, subdivision development, access routes for evacuations and firefighting, the potential need to focus on areas with difficult terrain (as they may be of most need of treatment), and a focus on erosion threats (see Group Working Session notes at the end of the chapter).

When we overlaid the selections from the two online maps, we identified 26 AUs that were common selections by 9-21 users (Figure 2.5). Using this initial set of 26 as a foundation, we built upon them by first looking at the two maps individually to ensure that the merging of the maps did not exclude critical feedback from either of the two maps (see Stakeholder AU Selection Rationale at the end of this chapter). As a result, we added two AUs from the utility burn probability map (AU 115, 24) identified as critical on one map but not the other. These were located at a high elevation in the watershed along the North Fork Mokelumne River, with south-facing slopes and high burn probabilities. As the result of comparing stakeholders' AU selections as they related to their relationship to the watershed (i.e., whether they lived and/or worked inside or outside the watershed) to the 28 that had so far been included, we added two that were high ranking (4-7 users selected, AU 40, 63). These two AUs are located near the South Fork Mokelumne River. We also added 4 AUs selected by EBMUD (AUs 148, 80, 69, 95), which are located downstream at the lower elevation of the study area, close to Pardee Reservoir.

In the next step of the process, we considered the results of the insect and disease mortality projects (see Appendix B) in the context of AUs. We initially added 14 AUs based on the insect and disease mortality projections, but through further discussion with the two committees and because many of these AUs were located within the wilderness and roadless areas, we reduced this number to two (AU 12, 133), a decision that was supported by one of the forest health experts that was engaged in the process. These two AUs were at very high risk for bark beetles damage and they are adjacent to Cole Creek.

The group also decided to add 3 AUs (35, 89, 146) in the WUI, the zone of transition between urban and forest land cover. Bill Haigh with the BLM designated these AUs as the "eye of the storm," an area that should be prioritized for forest treatment to reduce community wildfire risk. In this same area, we removed AU 79 as there are no roads to facilitate treatment and it is steep (slope >35%). Sediment modeler Bill Elliott questioned the lack of north-facing slopes, which are at greatest risk for both high flame lengths and sediment but also have less infrastructure on them, and as a result we added AUs 105, 109, and 144 on the North Fork Mokelumne River. For similar reasons, we also added AUs 59, 61, and 64 on the South Fork of the Mokelumne River where some of the highest flame lengths, sediment loads, and burn probabilities were modeled and where we assumed there would be a potential threat to Pardee Reservoir.

Figure 2.7: Stakeholder selection of AU subwatershed areas to treat



2.3.3 Discussion

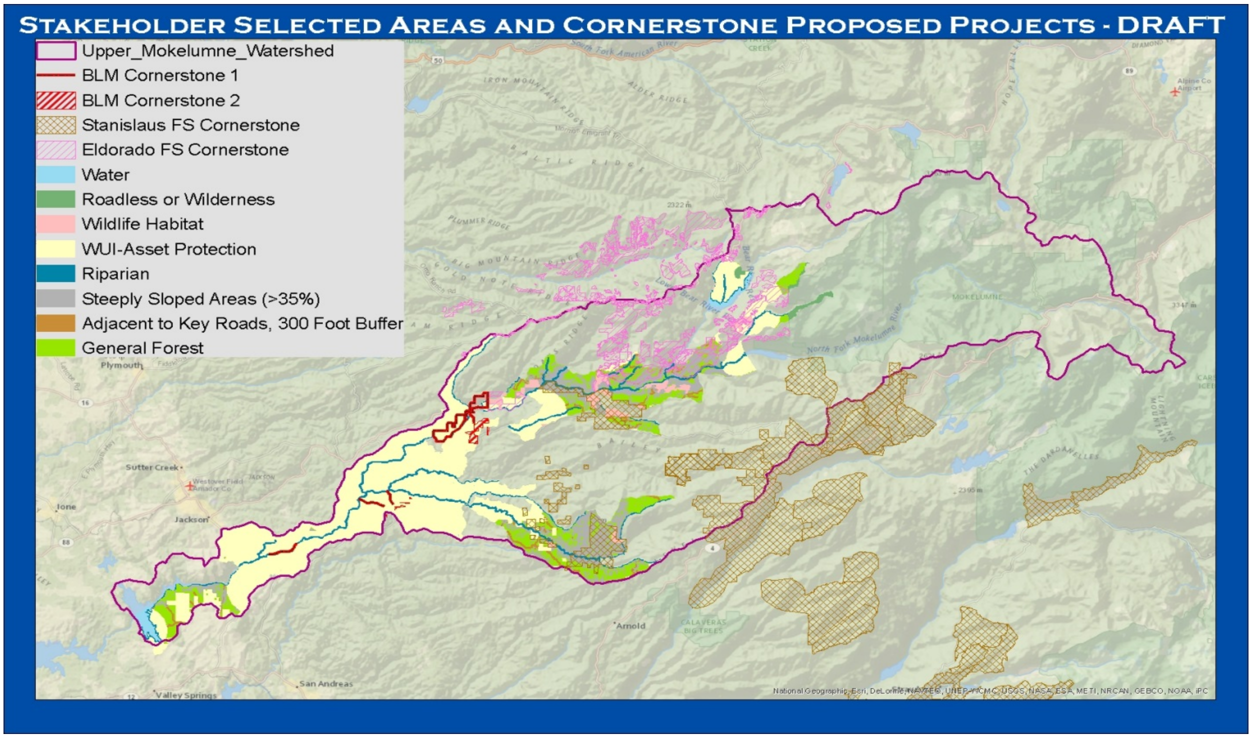
The collaborative selection of AUs for forest treatment allowed multiple opportunities for stakeholder input and led to a greater stakeholder understanding of the fire and sediment model results. As discussed in a later section, we had only one opportunity to run the fire and postfire sediment models for a hypothetical treatment scenario, so it was vital that the stakeholder values and opinions were captured, to the extent possible, the first time around. The stakeholder input identified assets and values within the watershed at risk from wildfire that were not included in the development of the two data layers the stakeholders used to select AUs. When compared to an AU selection process that only factors in the results from the models (Figure 2.6), the stakeholder selection included more forest around the South and North Forks of the Mokelumne River. In the model-based selection, the areas in the WUI with low erosion risk were not included. Likewise, a large area in the center of the watershed in the mid-elevation range was not included in the stakeholder selection. While this may result in a lower reduction in sediment from the posttreatment model run, the stakeholder process accounted for additional assets in the urban areas, and the potential cost of fire impacts to these assets was large. With more time and funding, it would have been an interesting exercise to run the model using a model-based selection, comparing the cost and benefit to the stakeholder selection. Another advance would be to create a cost surface of treatment compared to assets to optimize treatments to be cost effective, but we did not have the data for those costs in time to incorporate it at that point in the analysis.

Compared to the planned USFS- and BLM-proposed project areas within the Mokelumne watershed, the stakeholder AU selection encompasses a much larger area, including lands outside of their boundaries (Figure 2.8 and Table 2.1). There is overlap between the planned treatments and the stakeholder selection of AUs. The USFS has at least some land in 22 of the selected AUs and 16 of these (73%) have USFS-planned projects. BLM has land in 26 selected AUs and seven of these (27%) have planned projects. The USFS treatments are located across their respective districts, which fall within and outside the watershed, with a focus on the mid-elevation southern boundary of the watershed and along the north-facing slopes along the North Fork of the Mokelumne.

The BLM treatments are small in comparison, as their lands are dispersed among privately owned parcels, and include an area along the North Fork Mokelumne, and stretches along the main stem of the Mokelumne River upstream of Pardee Reservoir. The lack of overlap in some areas of the watershed highlights the fact that the USFS and BLM treatments focus on a range of objectives beyond those that are the focus of this analysis, and these projects were planned prior to the much higher resolution modeling that was performed as a part of this analysis. Further, their projects are limited to the area of land management they oversee. This study, in contrast, spans the entire watershed and uses advanced fire modeling, including burn probability and fire spread, across all ownership types.

The lessons learned from our modeling of fire and sediment in the watershed can help inform the prioritization and planning by the ACCG, Fire Safe Councils, USFS, and BLM. The data from the analysis will be available for the organizations to use in their own internal planning, as well as the broad range of topics covered in the analysis, including potential costs. As additional investments in treatments begin to be realized within the watershed, the data from this analysis will help the land managers and investors decide on the most effective and efficient investments.

Figure 2.8: Planned forest management on USFS and BLM land overlaid on the AU stakeholder treatment selection



Note: the AU stakeholder selection shows the land use classification, which later determined the treatment code.

Table 2.1: Breakdown of treatments by land type and ownership

Land type	USFS ownership	BLM ownership	Other ownership/private
Water	33%	2%	66%
Wilderness-roadless	83%	0%	17%
CSOPACs	97%	0%	3%
Riparian	27%	23%	50%
Transmission lines	32%	5%	63%
Key roads	11%	8%	81%
Steeply sloped	28%	20%	52%
Parcels with structures	0.04%	0.42%	99.54%
General forest	25%	10%	65%
All Land Types Combined	*24%*	*12%*	*64%*

Note: CSOPAC = California Spotted Owl Protected Activity Centers

2.4 Treatment Scenario Development

2.4.1 Selecting Land Types for Treatment

Following the completion of the current-condition, or baseline, model runs in all of the modeling processes, our efforts shifted to the development of a treatment condition scenario on which we could base the subsequent model runs. Given that we were limited to one treated-condition fire and sediment modeling run, our goal was to define a treatment scenario that would ensure that the modeled treatments encompassed enough of the landscape that their effectiveness could be assessed, while still allowing us to tease out key details at a smaller scale. As a first step, we reviewed how the fire model inputs would be adjusted to incorporate forest treatments. To this end, Phil Bowden, the Technical Committee member in charge of running the fire model, developed a matrix showing how he would integrate the treatments into the model (Figure 2.9).

The fire model bases its outputs on a single vegetation change (i.e., pre to post) rather than a series of changes over time. As such, it became clear that we needed to model the desired end result of the treatments on forest conditions, instead of breaking the treatment implementation stages into a multi-year process that may more-accurately represent the progression of treatment implementation. Additionally, the fire model can only process the desired end state of the forest with regards to vegetation, rather than inputting discrete treatment types directly into the model (e.g., mechanical thinning). That shifted our focus from the types of treatments to include to what the end goal of the treatment would be, highlighting the need to work with local land managers to learn how the treatments they implement impact vegetation. For example, hand thinning would be preferred in some situations over mechanical thinning, but the two treatment methods can result in similar end-states in terms of the forest structure. We worked with local land managers to determine the posttreatment forest conditions for the area so we could represent the desired final conditions in the fire model. After speaking with land managers that oversee forest management in either the lower or upper elevations of the watershed, we developed the following list of land types that would likely have differing approaches to treatments and therefore result in different forest stand conditions:

1. Wilderness and Roadless areas
2. Protected Activity Centers (PACs)
3. Riparian areas
4. Wildland-Urban Interface (WUI), Asset Protection areas, and Strategically Placed Landscape Area Treatments (SPLATs)
5. Steep slopes
6. Near key roads
7. General forest

The Advisory and Technical Committees worked together to refine the definitions of the included land types and codes that, based on the original matrix (Figure 2.9), would be most appropriate to apply in the modeled treatment scenario. The final matrix and codes that would be applied to the watershed can be found in Figure 2.10.

2.4.2 Geographic Application of Treatments

To determine where to place the treatments across the Mokelumne watershed, we convened a special Treatment Team composed of Technical Committee members as well as other regional experts who to date had not been involved in the analysis. In preparation for this meeting, we created a GIS data layer that broke the watershed into the seven categories listed above. For areas that could belong in two or more of the seven categories, we created a hierarchy of land types based on the category that would most restrict the level of treatment (e.g., we designated as Wilderness a steeply sloped parcel within the Wilderness area). We designated any parcel of land that did not fit into the six previous categories as general forest. We also specified the inclusion of the primary transmission line corridor that bisects the watershed and has a specific treatment strategy applied to it. The roughly 100,000 acres that the stakeholders selected for the treatment area break down into the following land types (see Table 2.1 for an ownership break down):

- General forest – 30.4%
- Steeply sloped – 29.8%
- Key roads – 15.8%
- Parcels with structures – 9.9%
- Riparian – 7.5%
- PACs – 3.0%
- Transmission line corridor – 1.5%
- Water – 1.2%
- Wilderness/roadless – 0.9%

In the end, the Treatment Team decided that the treatment conditions should be run at the full extent of the stakeholder-selected AUs (Figure 2.11). This was predominantly because we only had one opportunity to run a treatment scenario in the models, and running it at the larger scale of the stakeholder-selected AUs would capture more details than a smaller-scale run would. The full 100,000-acre treatment scenario would allow us to more easily tease out details from the results, such as a comparison between similar treatments in distinct locations in the watershed to see how treatment effectiveness may differ and why. These distinctions could help refine where further analysis should focus. Likewise, it was also important to not treat the entire watershed, as treatments can affect fire behavior in adjacent lands, and understanding the degree to which those lands are affected is important.

The incredible amount of stakeholder input we received during the development of the AU selections signified the importance of the selected areas; removing some of the selected areas from the treatment scenario would have been very difficult. Similarly, it would have been very time and resource intensive to address the multitude of management restrictions that would have been necessary to include in a more-focused treatment condition. By running the scenario at this scale, we were later able to review the economic value of certain areas, the cost of the treatments, and how the treatments affected flame length and sediment production. Interestingly, the distinct "fingers" of treatments across the watershed provided insights into where treatments had the greatest shadow effect on the burn probabilities of adjacent untreated areas (see Appendix A for more details).

Figure 2.9: Modeled treatment coding steps

MOKELUMNE AVOIDED COST ANALYSIS (MACA)
MODELED TREATMENT CODING STEPS

Step #1 Pick the unit to treat....................

LANDFIRE Disturbance Code Information

The newest version of the LFTFC (LANDFIRE Total Fuel Change) Tool for ArcGIS 10 is being used to create and calibrate the needed FARSITE landscape files (LCP) so FlamMap5 and FSim can simulate fire behavior and spread.
LFTFC Info: http://www.frames.gov/partner-sites/niftt/tools/niftt-current-resources/
Fuel Disturbance Layer (FDIST) The FDIST is the input layer that simulates recent disturbances and is required when using the LFTFC. A FDIST is available from the LANDFIRE Data Distribution Site for disturbances prior to 2009. LANDFIRE Info: http://www.landfire.gov/
The use of the FDIST grid values will allow MACA to account for future disturbances such as prescribed fire or other vegetation treatments. This level of detail seems to be appropriate for this landscape scale analysis but would be of questionable value at the project scale.

The grid value of FDIST is denoted by a 3-digit integer which identifies the disturbance type, disturbance severity, and time since disturbance, respectively. That is, the first digit identifies the disturbance type (Table 2); the second digit identifies the disturbance severity (Table 3); and the third digit identifies the time since disturbance (Table 4).
LANDFIRE used Time Since Disturbance (TSD) to account for the transition of fuels through the first 10-years following disturbance. The classification system was stratified by geographic area as productivity in Hawaii and the Southeastern Unities States is substantially higher than the rest of the Unities States. *TSD for the 1st round of MACA modeled treatments the default code will be #2.*

Table 5 is for MACA use and deals with the modeled Treatment of Canopy Fuels.

Final Modeled Treatment Code Structure for MACA

MACA scenarios will simply create a geospatial file (shape, geodatabase) with polygons and at least these 3 attribute fields: **1)** Unit_num, IU or AU number; **2) FDIST**, the 3 digit FDIST code as described in the following three tables; and **3) CFTP**, Canopy Fuel Treatment Priority.

pb 1/4/2013

Step #2
Pick the treatment type

Table 2 Five disturbance types used by LANDFIRE For MACA choose Highlighted only

Disturbance Types and Effects	FDIST Grid Values	Examples
Fire– alters canopy fuel characteristics and surface fuel loads	100 series (e.g., 1XX)	Wildfire and Prescribed Fire
Mechanical – rearranges or adds fuel to the fuel bed	200 series (e.g., 2XX)	Mastication, lop & scatter, piling
Mechanical – removes fuel from the existing fuel bed	300 series (e.g., 3XX)	Timber harvest or other biomass removal treatments
Wind – alters canopy fuel characteristics and surface fuel loads	400 series (e.g., 4XX)	Any blow down event
Insects – modifies canopy fuel characteristics	500 series (e.g., 5XX)	Mountain pine beetle

Step #3
Pick the level of treatment

Table 3 Disturbance severity classes used by LANDFIRE If Green Highlight complete Step #5

Severity class and Effects	FDIST Grid Values	Examples
Low – less than 25% above-ground biomass removed	10 series (e.g., X1X)	Under burns, light thinning
Moderate – 25 to 75% above-ground biomass removed	20 series (e.g., X2X)	Mixed-severity burns, moderate thinning
High – more than 75% above-ground biomass removed	30 series (e.g., X3X)	Stand-replacement burns, clearcuts and seed tree

Step #4
Default 1st round of Modeled Treatments

Table 4 Time since Disturbance (TSD) classes used by LANDFIRE default for 1st FDIST is Highlighted

Time Since Disturbance (TSD) Classes		
Hawaii and Southeastern US	Remainder of US	FDIST Grid Values
Less than 1-year	Less than 5 (right after burn)	1 series (e.g., XX1)
1 to 3 years	1 to 5 years (2.5 year midpoint)	2 series (e.g., XX2)
3 to 10 years	5 to 10 years (7.5 midpoint)	3 series (e.g., XX3)

Step #5
Pick the level of Canopy treatment

Table 5 Canopy Fuel Treatment Priority for severity classes Low (10) and Moderate (20) only.

Canopy Fuel Treatment Priority	CFTP Value	Examples
Low – canopy treatment is not important or is restricted	1	light under burns, piling of existing surface fuels only
Moderate – Canopy treatment is somewhat important	2	GTR 220 type of treatments
High - Canopy treatment is very important; goal is to greatly reduce crown fire.	3	Shaded Fuelbreaks, WUI Treatments

1

Figure 2.10: Matrix for treatment coding

Select area ==>	Treatment type ==>	Level of treatment ==>	Level of canopy treatment
	100=wildfire and prescribed fire	10=low under burns, light thinning	1=low, light under burns, piling of existing surface fuels
	200=mechanical mastication, lop & scatter, piling	20=moderate, mixed severity burns, moderate thinning	2=GTR 220 type treatment
	300=mechanical timber harvest or biomass removal	30=stand replacing burns, clearcuts, seed tree	3=shaded fuelbreaks, WUI treatments

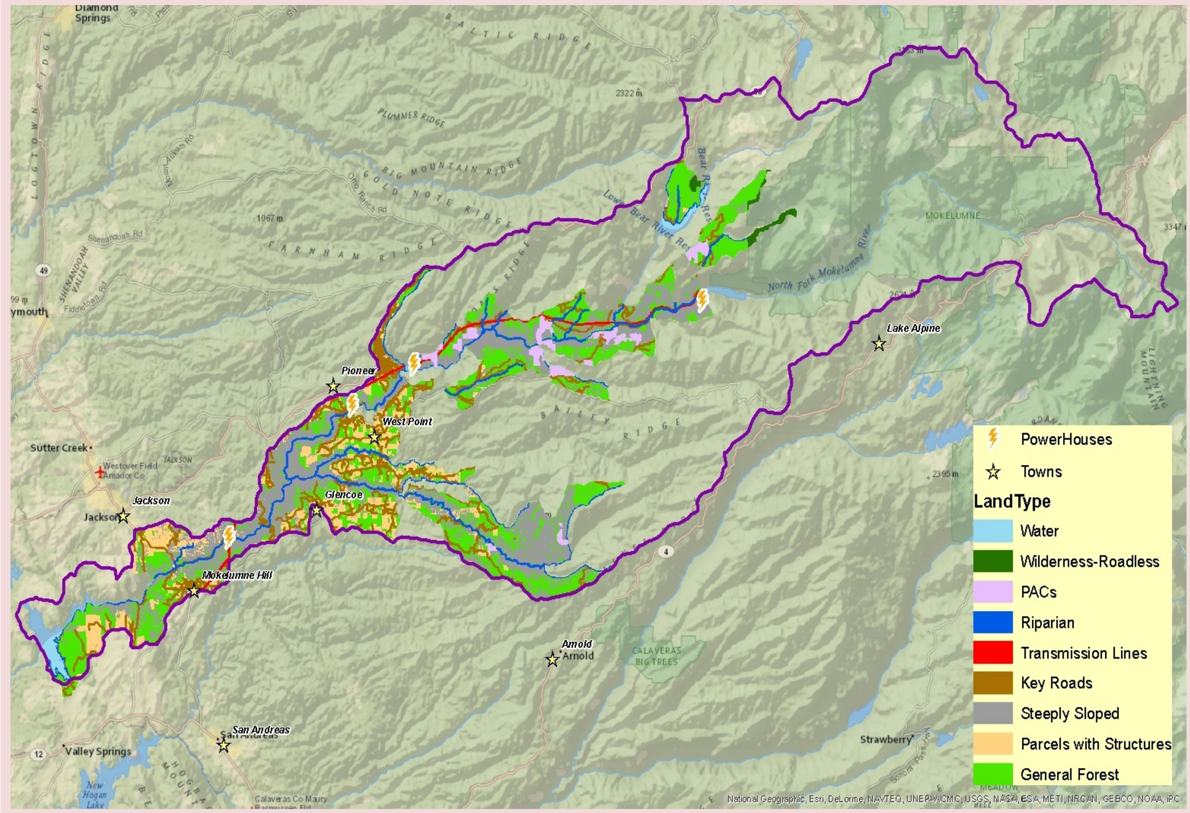
Example:	Mechanical timber harvest with moderate thinning in the GTR-220 style =	322

End Treatment Guide

Vegetation	Wilderness, Roadless, etc.	WUI, Asset Protection, SPLAT	PACs	Riparian Areas	General Forest	Steeply Sloped Areas (> 35%)*	Adjacent to key roads
Forested Lands	111	323	111	311	322	322	323

*** Areas within 0.5 miles of a road can be cable treated.**
Areas beyond that may be either helicopter treated or hand thinned and then prescribed burned.

Figure 2.11: Stakeholder-selected treatments in the Mokelumne watershed



References

Ager, A.A., Finney, M.A., Kerns, B.K., and Maffei, H. 2007. "Modeling wildfire risk to northern spotted owl habitat in Central Oregon, USA." *Forest Ecology and Management*. 246 (1): 45-56.

Andrews, P.L., and Butler, B.W. 2006. *Fuels Management-How to Measure Success: Conference Proceedings*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41.

Finney, M.A., Seli, R.C., McHugh, C.W., Ager, A.A., Bahro, B., Agee, J.K. 2007. "Simulation of Long-Term Landscape-Level Fuel Treatment Effects on Large Wildfires." *International Journal of Wildland Fire*. 16: 712-727

U.S. Department of Agriculture. 2011. "Purpose and need for action and proposed action-Sagehen project." Sagehen Project: Purpose of and Need for Action and Proposed Action. http://sagehen.ucnrs.org/blogs/SagehenForestProject/2011/7-12-11_new/Sagehen_Draft_PA_P&N_2011_07_07.pdf.

Materials from the Selection Process

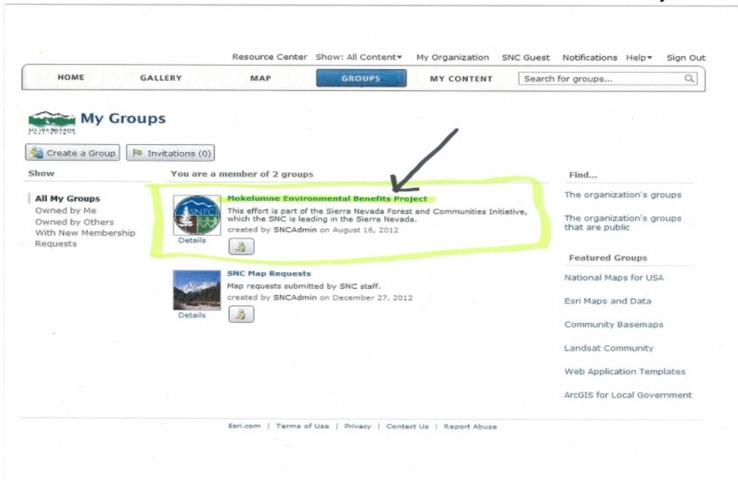
Online GIS Participation Instructions

ArcGIS instructions for how users would select forest treatment areas based on model results and risks to water infrastructure (two maps: utility mean burn probability; mean fire and erosion risk).

1. Log on to the page

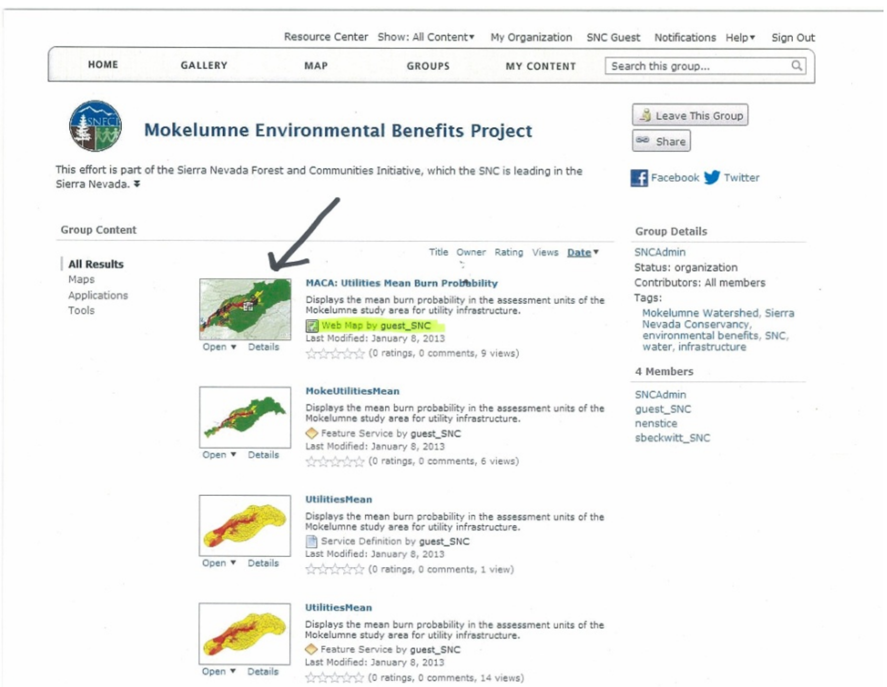
2: Click on Groups

3. Click on Mokelumne Environmental Benefits Project

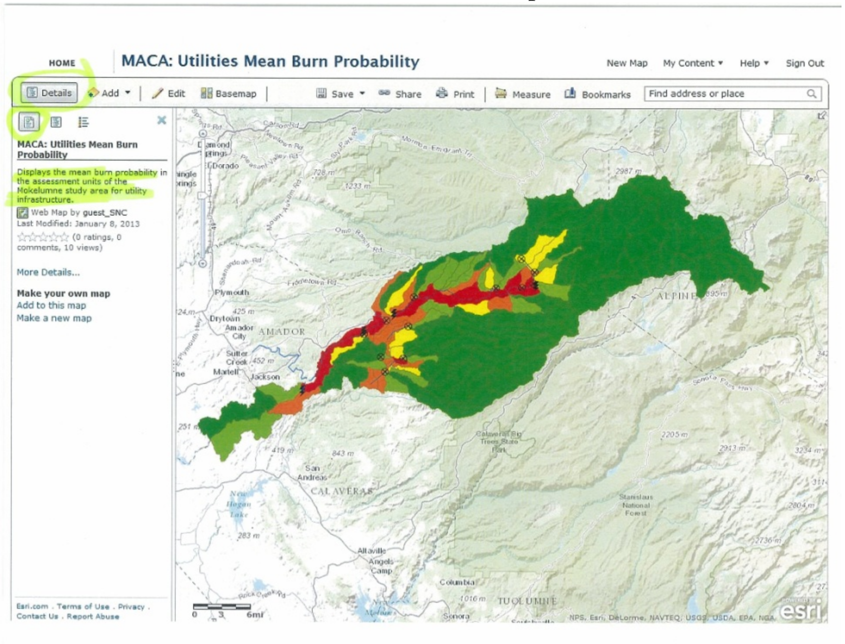


4. This is where all the individual maps will be located. For each of the four maps you will select AUs for, please select the one you are ready to work on by clicking the picture next to it. Make sure it says "Web Map" as highlighted below. The map names will be:

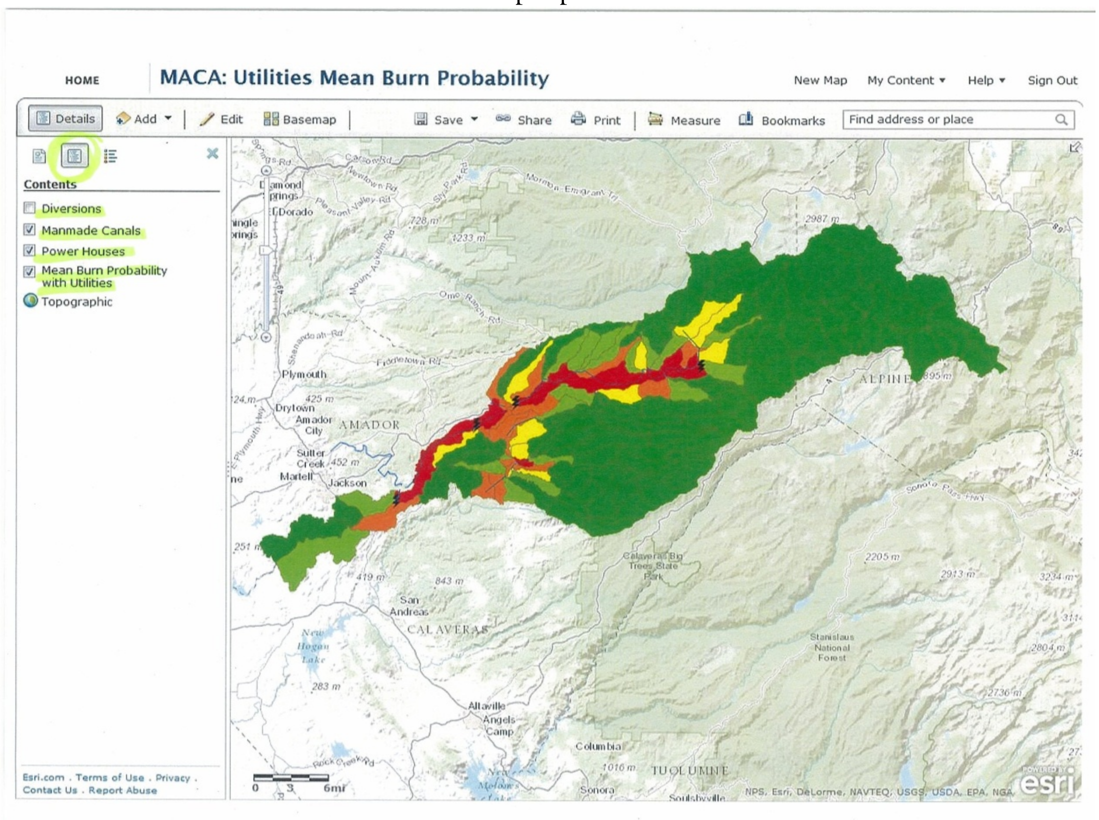
- MACA: Utilities Mean Burn Probability
- MACA: Mean Fire Erosion Risk
- MACA: Building Count
- MACA: Erosion and Intakes



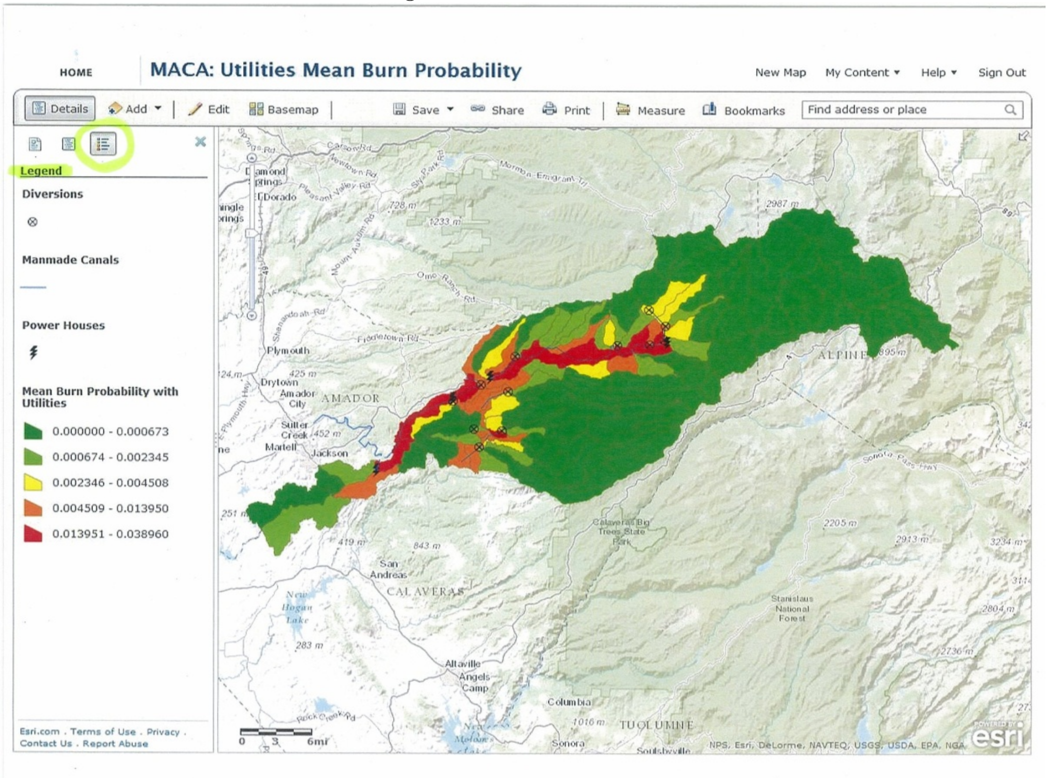
5. First tab under Details describes the map



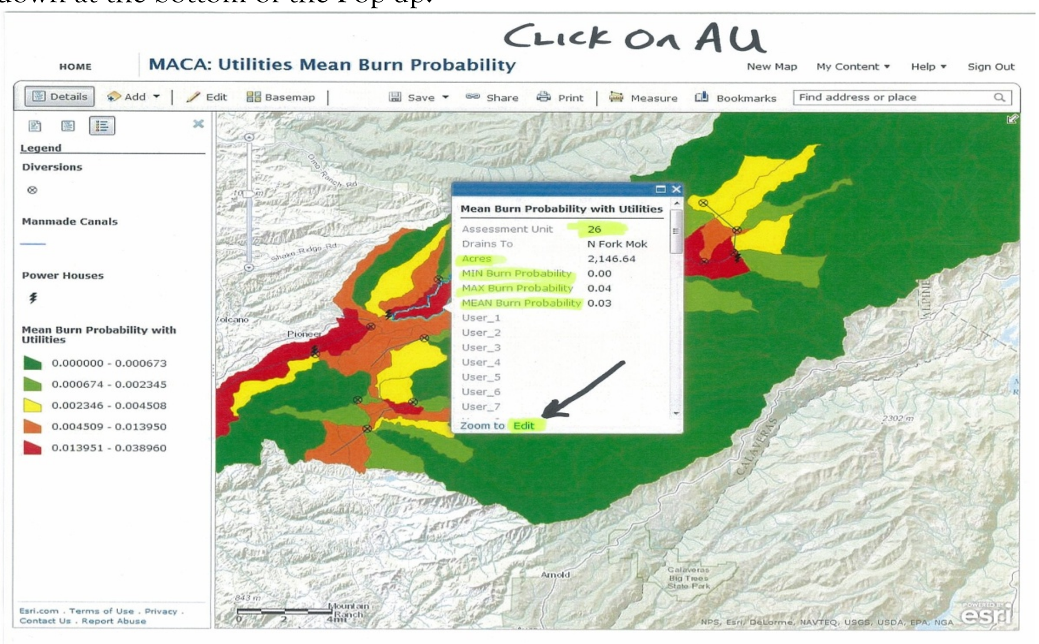
6. Second button under Details shows the layers available, which you can click on and off. Here I clicked Diversions off for demonstration purposes.



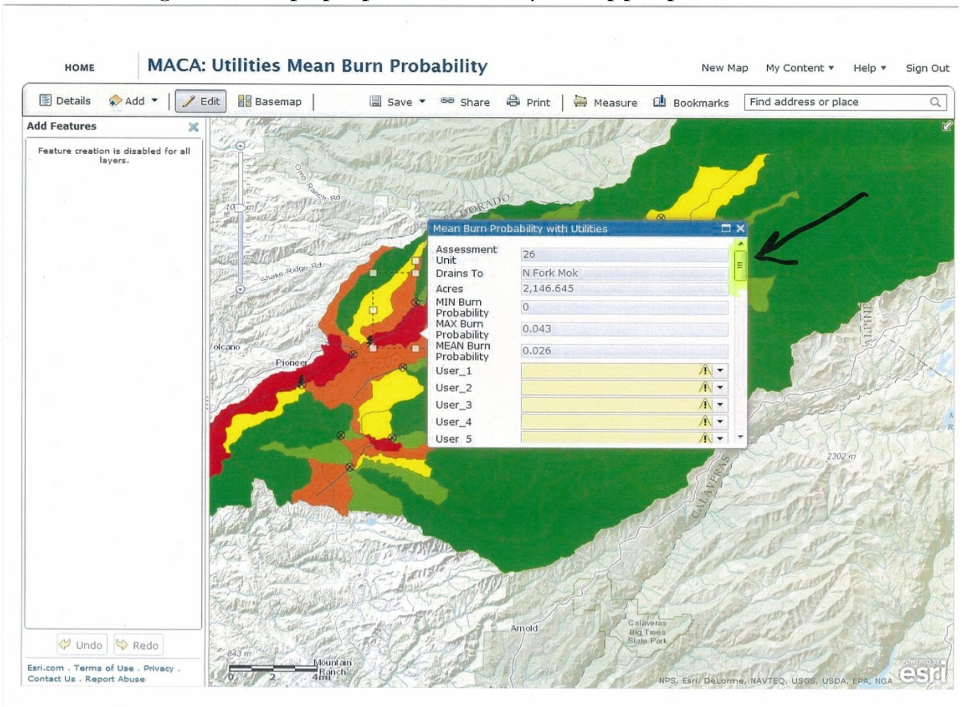
7. The third button shows the legend.



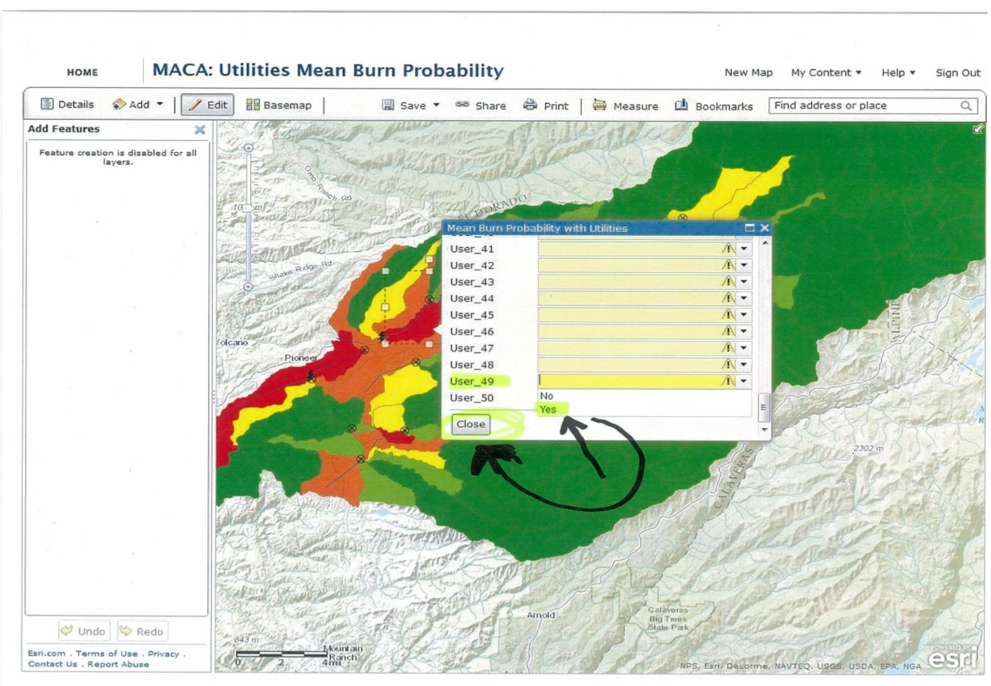
8. Once you click on an AU (zoom in or pan as necessary using the scroll bar on the left of the map), a Pop-up menu shows up. Here you can double check that you clicked on the correct AU you can see some of the attributes of the AU, including how many acres are in it and the min/max/mean burn probability of the AU. If you want to say "Yes" to this AU, click on EDIT down at the bottom of the Pop-up.



9. The Pop-up will change to what is below, where each user has a drop down menu. Use the scroll bar on the right of the pop-up to scroll to your appropriate user ID.

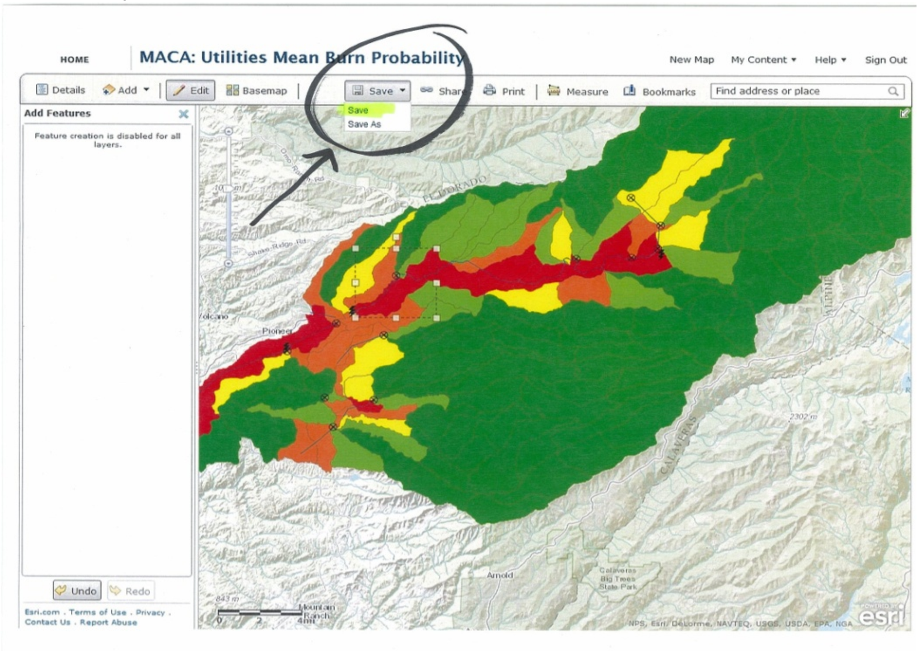


10. Once you find your User number (in this case user 49), click the drop down menu and select yes. It will set on yes, then you can hit close. Continue picking the AUs for selection on this map by repeating steps 8-10. I recommend saving after every 3-5 AU changes, which is shown under step 11.

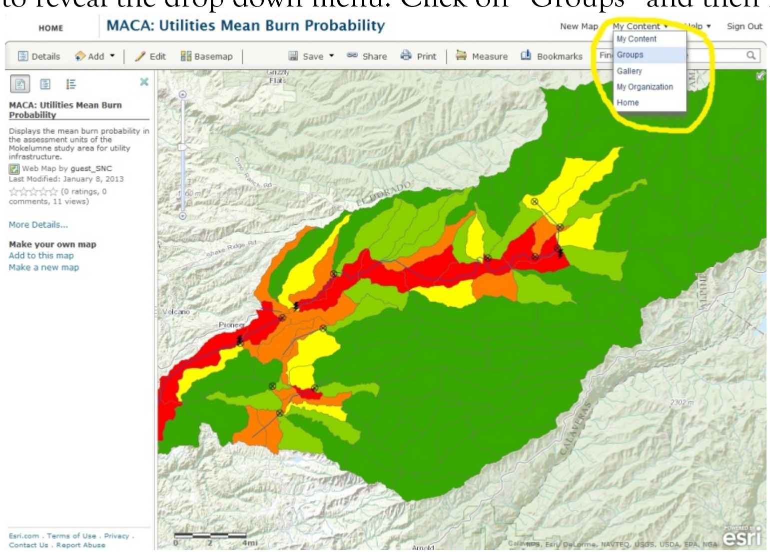


11. To save, click the Save button above the map, revealing a drop down menu. Please select "Save" only, not Save As.

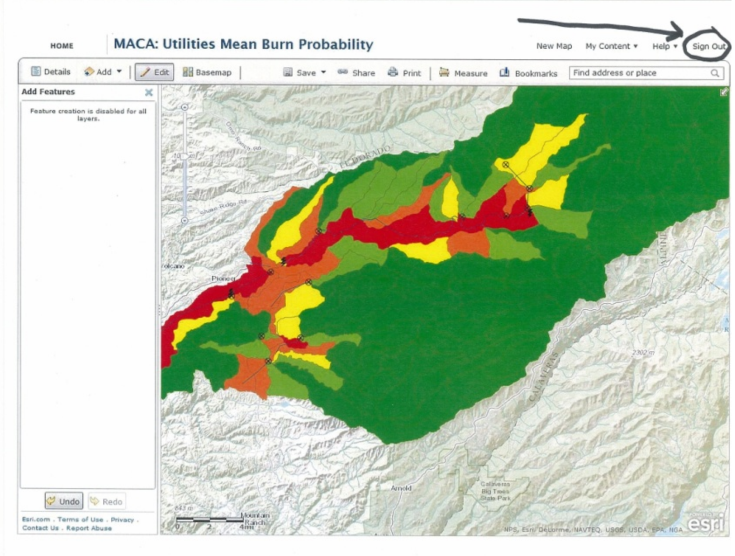
- If you are still selecting AUs, return to **step 8**.
- If you are done with this map but want to start working on another map, **go to step 12**.
- If you are done for this session, continue to **step 13**.



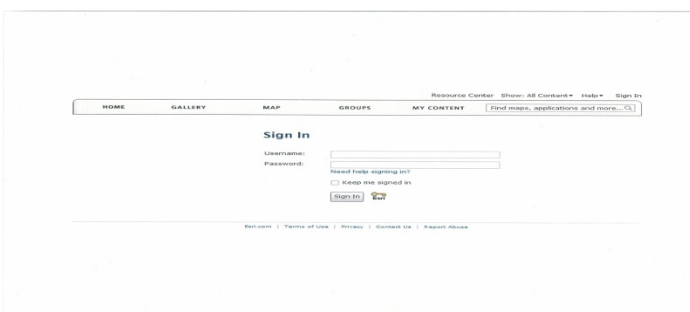
12. Once you have saved and you want to go to the next map, click on My Content in the top right to reveal the drop down menu. Click on "Groups" and then return to **step 3**.



13. To sign out, click Sign Out in the top right of the screen.



14. After you sign out, you will see the following screen and your session has ended. You can go ahead and close the window/tab/program.



Group Working Session on AU Selections for Treatment

January 10, 2013

Group 1
Identified clusters

1. 31,86,85 – High amount of recreational use, subdivision development at top (north side), PG&E infrastructure, existing community partnerships to treat, located in a steep inner canyon
2. 82,26,135 – High fire risk, high recreational use, difficult to contain fire spread in this canyon location, indirect effect to infrastructure
3. 136,95,103,81 – High sediment impacts
4. 105,144,109 – FDPA area i.e. CAL FIRE, sedimentation, Cornerstone, spread event from this location would be difficult to suppress
5. 78,75 – Steep canyon, canyon high risk for spread, containment is an issue

Group 2
Also identified clusters

1. Access routes for evacuation and firefighting: 112,107,101,102,104,115,84,20,10
2. Direct erosion threats to Pardee: 78,68,72,74,148,73,72
3. Upstream erosion threats to Pardee: 61, 40, 41, 63
4. Direct threats to Tiger Creek facility: 136,81,82,83,22,31,26

Group 3
Selection themes, no prioritization determined yet

Use red/orange cross-hatch on Erosion map (#3) to select AUs
Use red/orange Building Count map (#4) to select AUs
Use red/orange areas in Mean Utility Burn Probability map (#2)
Overlay all of the above with Burn Probability map (#6) to determine priorities.

Common AUs for Groups 1 and 2 = *26, 31, 78, 81, 82, 136*

PREPARED BY: Tim H.
DATE: 1-9-2013

GROUP 1

MEAN FIRE EROSION RISK
*103 REASON – WUI W/ IT. LOTS OF EROSION & FUEL HAZARDS. LOW ROAD DENSITY. SUB-DIVISION AT TOP (NORTH SIDE) BUILDING COUNT. HIGH RISK
#31 TIGER CREEK – FS PROPOSED TREATMENTS BELOW PIONEER; ~~HIGH~~ POTENTIAL FOR FIRE STARTS DUE TO RECREATION. BUILDING COUNT LOW. AUs.
BUNDLE 31 + 85 & 86, HIGH RISK & POTENTIAL FOR WILDFIRE. STRUCTURES, COLLABORATION W/ FS CA; COMMUNITIES PROTECTION OF ~~[illegible]~~ STRUCTURES, PARTNERSHIPS W/ PVT & GOV'T LAND OWNERS. PG&E, POWER LINES
TAKE INTO ACCOUNT ADJACENT AUs OR SELECT AU FOR STRATEGIC REASONS. e.g. BUNDLE 70/41/63/61/& 62.

#128 – ~~HIGH~~ FIRE RISK, LOW ROAD DENSITY, LOW INFRASTRUCTURE,

LOOK AT HIGH FIRE RISK, INFRASTRUCTURES, COMMUNITIES, MAP #3 CROSS HATCHED AREAS.

82, 26, 135, 103, 95, 136 & 81
(SEDIMENTATION BE ISSUE
CONTAINMENT SO IT DOES NOT CREATE ↑ SEDIMENTATION FROM OTHER AUs.
#109 – HIGH REC USE AREA. 144, 105 — CORNERSTONE PROJECT AREA;
DIFFICULT TO CONTAIN WILD FIRE THUS ↑ SEDIMENT,
DIFFICULT TO IMPLEMENT.

1/9/2013

GROUP #1

CAL FIRE & ARDP

SELECTION OF AUS FOR TREATMENT

Priority	AU #	Reason (Explain with brief notes)
1	31, 85, 86	RECREATION / HIGH RISK, POWERLINES, INFRASTRUCTURE, ~~31, 85 & 86~~ COMMUNITIES, PARTNERSHIPS (FS CA)
2	26, 82, 135	HIGH RISK, HIGH RECREATION, DIFFICULT TO CONTAIN FIRE. PG&E etc. STEEP SLOPES
3	103, 95, 136, 81	HIGH RISK, PROXIMITY TO INFRASTRUCTURE.
4	109, 105, 144	
5	75, 78	COVERAGE / CAL FIRE INCLUDE: 136, 135, 82, 75, 103
6		

GROUP 2

FIRE - INDUCED SEDIMENTATION
EFFECTS ON INFRASTRUCTURE
" " STORAGE

WUI

9) SAFETY OF TIGER CREEK FACILITY & ACCESS ROUTE
176
81 - 83
22
31
26

1) ACCESS ROUTES
112, 107 BEAR R. RD
101, 102, 104, 115 - ELLIS RD.
84, 20, 19 - PANTHER

2) EROSION RISK TO PARDEE N SLOPE HIGHER
78, 68 - ~~HIGH~~ EXT. EROSION
74 - MED HIGH EROSION, CLOSE TO PARDEE
148, 73, 72
S. SLOPE HIGHER

3) HIGH FIRE EROSION NOT FILTERED BY PEDE, BUT EARTHEN EM. PARDEE
41, 63, 59, 40, 60 S. FACING SLOPES

INCLUDE PH'S ON UTILITY BURN MAP
NEED HIGH-TENSION LINE INFRASTRUCTURE
EVACUATION ROUTES/ACCESS ROUTES

GROUP 2

SELECTION OF AUs FOR TREATMENT

Priority	AU #	Reason (Explain with brief notes)
1	112	ACCESS ROUTES FOR EVACUATION & FIRE FIGHTING
2	107	
3	101	
4	102	
5	104	
6	115	
7	84	
8	20	
9	19	
10	78	DIRECT EROSION THREAT TO PARDEE - ~~HIGH~~ EXT. RISK
11	68	"
12	72	" - ~~HIGH~~ MED. RISK, N. SLOPE
13	74	" - HIGH RISK, S SLOPE
14	148	"
15	73	"
16	72	"
17	61	UPSTREAM EROSION THREAT TO PARDEE - S. SLOPE EXT. RISK
18	40	" - "
19	41	" - N. SLOPE EXT. RISK
20	63	" - "

Priority	AU #	Reason (Explain with brief notes)
21	136	DIRECT THREAT TO TIGER CREEK FACILITY
22	81	"
23	82	"
24	83	"
25	22	"
26	31	"
27	26	"
28		
29		

Group 3

SELECTION OF AUS FOR TREATMENT

Priority	AU #	Reason (Explain with brief notes)
1		· Red/Orange in cross-hatch on Map 3
2		Red/Orange on map 4 : 51, 86, 77, 78, 73, 89, 30
3		~~A1~~ Red/Orange Map 2 but only if ∃ fire probability. 76, 77, 78, 79
4		– all overlaid w/ Map 6 to determine priorities
5		

Stakeholder AU Selection Rationale

AUs with14-21 Selections

21 selections: AU 78

These are the AUs that have been marked as highest priority for treatment. Of these AUs, AU 78 was selected the most often for treatment (21 selections). 10 people chose AU 78 b/c of the location of utilities within the selection, and 11 people chose it because of fire erosion risk. There was a high degree of overlap (9) in the selection process, meaning that numerous individuals chose AU 78 for both utility and fire erosion risk. David E: prioritized AU 78 as second tier, "reduce direct risk of fire to utility infrastructure". Kim C selected it as top pick, coupled with AU 75: "Tiger Creek Afterbay is one of the primary vulnerable points in the watershed with high levels of sedimentation and no protection between PG&E and EBMUD's system." During the TC AU Selection meeting, Group 1 likewise chose 78, 75, however they marked it as the lowest priority cluster. Reasons given were that they are located in a steep canyon, with lots of infrastructure. John H placed AU 78 under Units Recommended for Fire Erosion Risk: "Highest probability. Near homes". Interestingly, those who did not participate in the TC Selection process set AU78 as lower priority. From BLM: selected it as 9th: "Understory thin" (AU 77 was selected in 8th position, for the same reasoning).

16 Selections: AU 77

The second highest chosen assessment unit was AU 77 (16 selections). In proximity, AU 77 is adjacent to AU 78. 12 people chose AU 77 because of the location of utilities within the selection, and 4 people chose it because of fire erosion risk. There was some overlap (4) in the selection process, meaning that some individuals chose AU 78 for both utility and fire erosion risk. It is noteworthy that although these AUs are adjacent, AU 78 was chosen at a significantly higher rate for fire erosion risk (11) than AU 77 was chosen for fire erosion risk (4). David E: prioritized it as second tier, "reduce direct risk of fire to utility infrastructure" John H. included AU 77 among AUs needing treatment because of Utilities located within the AU. His reasoning was "second highest priority to burn. Near homes. Water quality".

For Fire Erosion, AU 78 was selected 11 times whereas AU 77 was only chosen 4 times. That means that 7 more respondents chose AU 78 as needing treatment over AU 77 for fire erosion risk. For Utilities, the overall total was 12 for AU 78 and 10 for AU 77. That means 2 more respondents chose AU 77 as needing treatment over AU 78 for utilities. This suggests that AU 78 displays a similarity to AU 77 but that AU 78 poses a greater risk to fire erosion than AU 77. AU 77, however, poses a slightly greater risk to utilities, reflecting the fact that 2 members included it as needing treatment under the utilities map.

14 Selections: AUs 31, 82

AU 31 and AU 82 tied for overall total with 14 selections. AU 31 is adjacent to AU 77. For AU 31, of the total 14 selections, 10 people chose b/c of Utility, 4 people chose b/c of Fire Erosion. Group 1 identified AU 31 as a highest priority cluster, along with AUs 85 and 86. The reasoning was because of High amount of recreational use, subdivision development at the top (north side), PG&E infrastructure, existing community partnerships to treat, and because it was located in a steep inner canyon. Group 2 identified AU 31 in its fourth priority cluster to treat, along with AUs 136,81,82,83,22, and 26. David E. chose AU 31 along with AUs 72,73,76,77,78,86,89,146 and 30 to "protect communities/areas with dense buildings". John Hofmann chose this AU for both fire erosion and utilities risk. His reasoning for choosing AU 31 for fire erosion was because it is "opposite the side of the river from moderate probability (AU 81) which may burn also and add erosion if it (AU 81) burns." He also chose this AU for utilities risk because it was "highest probability to burn. Nearby homes. Influence electric water quality."

For AU82, of the total 14 selections, 5 people chose b/c of Utility, 9 people chose b/c of fire erosion. In the TC Analysis meeting, Group 1 included AU82 in their second cluster, along with AU 26 and AU 135. Their reasoning was that these clusters are in high fire risk areas, high recreation areas. Additionally, they reasoned that these AUs were in areas where if a fire were to occur it would be difficult to contain, and there's risk of an indirect impact on infrastructure. Group 2 included AU 82 in their fourth cluster, along with AUs 136,81,83,22,31 and 26. Their reasoning was that these AUs were close to the Tiger Creek Facility and because of the threat to PG& E structures (power lines, etc). David E included AU 82 in his second cluster of AUs that should be treated to reduce direct risk of fire to utility infrastructure. John H included AU 82 in his selection for units to be treated b/c of utilities: "highest probability to burn, close to powerhouse. Close to homes. Flume."

<u>9-13 Selections</u>

13 Selections: AU 91

These are the AUs that have received a number of selections, but aren't put into the top priority. With 13 selections, AU 91 received 8 selections for Utility and 5 for fire erosion. Interestingly, none of the groups within the TC AU Selection meeting chose AU 91 for treatment during the selection process, but participants chose this AU for treatment on the online GIS map. BLM included AU 91 as their 9th treatment priority, with the note: "understory thin". Jim C selected AU 91 as selection #5 for utilities. The following participants chose AU 91 for treatment: For Fire Erosion: CAL FIRE, Phil B, Reuben C, BLM, Jim C. For Utility: CAL FIRE, David E, Phil B, Bruce G, Reuben C, Stanislaus FS, BLM, Jim C.

12 Selections: AUs 73,75,76,88,103

AU 73 received 8 selections for Utility and 4 selections for fire erosion. In the TC AU Selection meeting, Group 2 included AU73 in their second cluster, along with AUs 78,68,72,74,148, and 72. Their reasoning was that these AUs were close to Pardee Reservoir and therefore had direction erosion threat to the reservoir. Within this cluster, the group prioritized the North –facing slopes (because they tend to have more fuels) over the South-facing slopes. David E chose AU 73 under this third cluster (along with AUs 72,76,77,78,31,86,89,146, and 30), because if treated it would protect community/areas with dense buildings.

AU 75 also received 12 selections, 3 were for Utility and 9 were for fire erosion. In the TC AU Selection meeting, Group 1 clustered AU 75 along with AU78 in its lowest priority cluster. Their reasoning was these AUs were in steep canyons where fire was at a high risk to spread, and fire containment is an issue. The following participants chose AU 75 for treatment: For Fire Erosion: CAL FIRE, Kim C, Barry H, Phil B, Kristen P, Frank M, Bruce B, Rick L, BLM. For Utility: Phil B, Reuben C, and BLM.

AU 76 likewise received 12 selections, 8 were Utility and 4 were fire erosion. David E included AU 76 (along with AUs 77,78,147,91,26,82,24,25,115,135,71, and 137) in his second prioritization group, with the reason that these AUs reduce the direct risk of fire to utility infrastructure. John H included AU 76 under AUs needing treatment for utility reasons: “medium probability to burn, near homes and communities. Recreational uses.” BLM ranked it as 5th priority: “Fuel break, understory thin, multiple parcels”.

AU 88 also received 12 selections, 7 were Utility and 5 were fire erosion. BLM included AU 88 as their 4th priority: “understory thin, multiple parcels”. Jim C included AU 88 as his 4th priority for fire erosion risk.

AU 103 also received 12 selections, 3 were Utility and 9 were fire erosion. In the TC AU Selection meeting Group 1 selected AU103 in their third cluster, along with AUs 136, 95, and 81. These clusters were chosen because of the risk of high sedimentation loads (specifically AU 81). David H included AU 103 for fire erosion risk, with the following note: “highest probability, just below a home track”.

11 Selections: AUs 30, 41, 72, 81

AU 30 was chosen 6 times for Utilities and 5 times for fire erosion. John H selected it for treatment because of utilities: “liability for homes from fires around powerhouses. Recreation” He also recommended it for treatment b/c of fire erosion risk: “uphill from a moderate probability (AU 81) but flatter and easier to treat. Although uphill will not prevent erosion downhill, it will help to reduce additional erosion from a wildfire that burns through AU81”. BLM made it their 10th selection: “fuel break, understory thin”. Jim C included it as his 4th selection for utilities, and 12th for erosion risk.

AU 41 also was selected 11 times, 3 times for utility and 8 for fire erosion risk. In the TC AU Selection meeting, Group 2 selected it (along with AUs 61, 40 and 63) in their third cluster because of these AUs’ direct erosion threat to Pardee Reservoir: “These AUs are found on the south fork of the river, where PG&E infrastructure would not be trapping sediment so there’s a pretty substantial threat to erosion affecting the reservoir. In this case, group 2 found the south facing slopes to be of high priority because they tend to heat up and burn and there’s a pretty heavy fuel distribution on both sides of the canyon”. Kim C included AU41 along with AUs 71, 70,62,61,63 and possibly 40- “these AUs show high fire severity and erosion adjacent to the South Fork. There is no protection (other than Tiger Creek Afterbay which is vulnerable) between this river channel and the EBMUD system. These AUs could be prioritized by slope, proximity to river, etc. but I just don't have the time to look that closely". David H included AU 41 as well under fire erosion risk: "highest probability and closest to communities"

AU 72 also was selected 11 times, 4 times for utility and 7 for fire erosion risk. In the TC AU Selection meeting, Group 2 included it in their second cluster (see AU 73 above for reasoning). David E included it in his third grouping, "protect communities/areas with dense buildings". John H said, "same as AU 77 but lower priority due to lower burn probability." AU 77 reads: "second highest probability to burn. Near homes. Water quality."

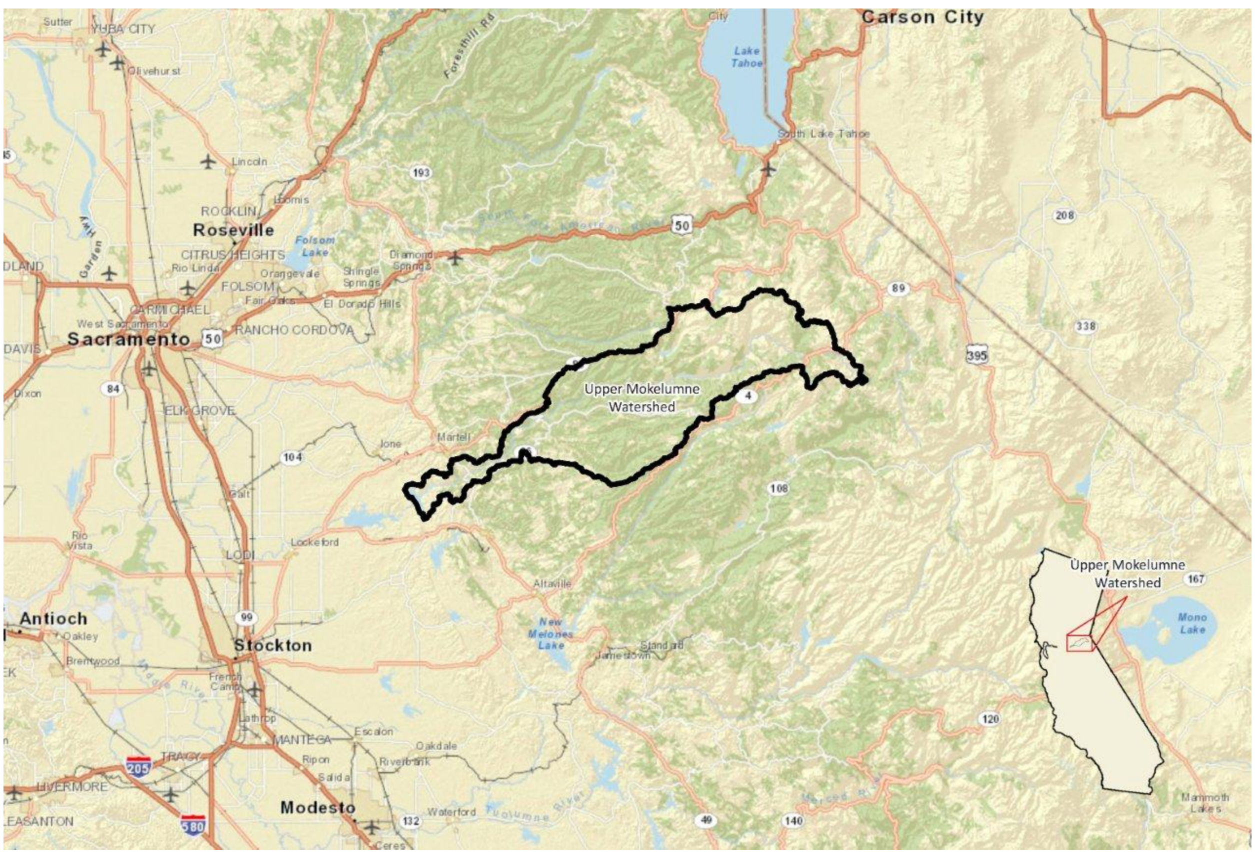
AU 81 likewise was selected 11 times, 7 times for utility and 4 for fire erosion. TC AU Selection meeting Group 1 noted it as being especially at risk for sedimentation loads. Group 2 also noted AU81 as being close to Tiger Creek facility and because of threat to PG&E structures (power lines, etc). See AU 31 above for reasoning. David E included it in one of his 1st groups along with 72, 74, 73, 148, 81, 82, 22, 26, 136, 84, 20, 19, 101, 104, 18, 115, 105, 46, 48, 11, 111, 3, 5, 116, 17, 43, 44, 15, 120, 121: reduce sediment risk within 10 miles upstream of facilities, combining postfire erosion risk with burn probability. Jim C included it as 4th choice for utilities.

With 10 selections: AUs 25, 48, 62, 71
With 9 selections: AUs 26, 37,39, 68, 86, 93
With 8 selections: AUs 98, 115
With 7 selections: AUs 24, 40, 95
With 6 selections: AUs 32, 46, 70, 74, 79, 80, 89, 100, 109
With 5 selections: AUs 18, 61, 83, 84, 92, 101, 105, 136, 148
With 4 selections: AUs 22, 38, 59, 67, 69, 110, 111

Chapter 3: Model Results—Fuel treatments effects on fire behavior, erosion, and debris flows

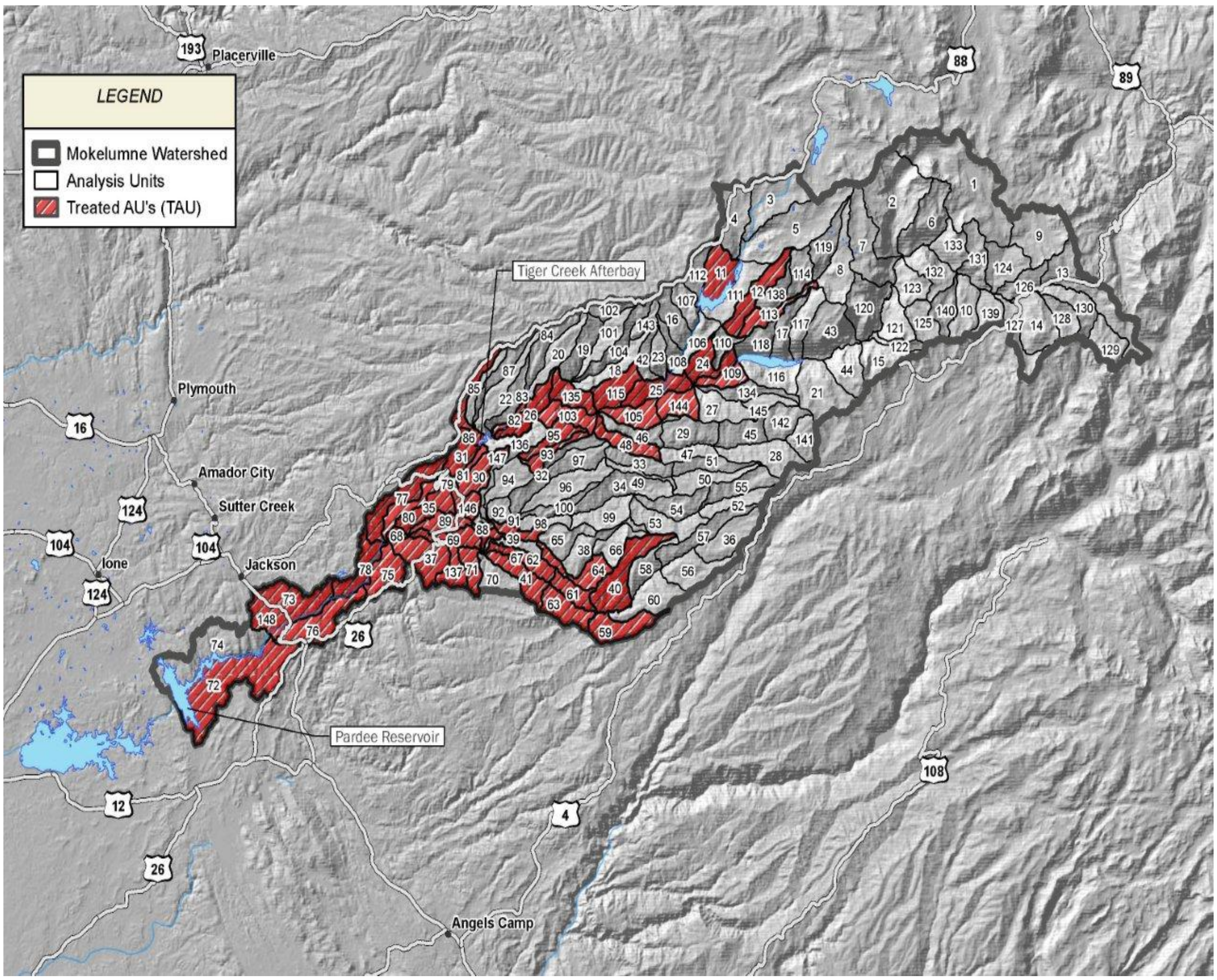
For this analysis we used a series of process-based models to represent existing wildfire and sedimentation conditions of the upper Mokelumne watershed, and then to estimate the effects of fuel treatments on fire behavior and erosion (Figure 3.1; see Appendices A-E for detailed information about the models). An effective fuel treatments program is expected to reduce the likelihood, intensity, and severity of fires, a hypothesis we tested by modeling specific changes to the vegetation within the treated analysis units (TAUs; Figure 3.2). The rationale and approach to the selection of the TAUs and the treatments within them are detailed in Chapter 2. We used wildfire and erosion modeling platforms, including FSim, FlamMap5 and GeoWEPP, to quantify changes in fire and sediment generation behavior resulting from fuel treatments.

Figure 3.1: Upper Mokelumne watershed boundary and regional location



The fire and GeoWEPP models were used to represent the existing (2012) Mokelumne watershed conditions. Then the modelers modified the fuel and vegetation conditions within the TAU locations and re-ran the models to estimate fire behavior, fire effects, and hillslope fine-sediment (<2 mm) erosion after treatment. No other changes to the models were made, ensuring that any differences between pre- and posttreatment results were due solely to the effects related to fuel treatments and not climate, fire history, or other inputs to the model. Each model attempts to accurately reflect very complex natural processes; as such, each has its own limitations and compromises. In the appendices we attempt to capture these limitations and assumptions so the reader can make his or her own judgments, and we compare the model results to real-world observations or literature reviews to appropriately frame the results. For this study, we erred on the side of caution and used more conservative numbers with the purpose of describing a scenario with minimal watershed damage, keeping in mind that it could be much more damaging than described on these pages.

Figure 3.2: Analysis units and treated analysis units for the treatment modeling scenario



Small-diameter hillslope sediment modeled in GeoWEPP is not the only source of postfire sediment. To capture a broader spectrum of the potential sediment sources that could be influenced by fire, we included two sediment models that represent the combined processes of gully erosion and debris flows, which in postfire landscapes are similar processes (Istanbulluoglu, 2003, 2004). The FERGI (Fire-Enhanced Runoff and Gully Initiation) gully erosion model focuses more on hydrology than does the debris-flow model. However, the FERGI model does not include volume estimates in its outputs; the average volume from documented gullies that formed in the Power Fire burn area was used. As described in Appendix E, the conditions surrounding the formation of the observed gully could overestimate gully volumes for gullies that form under more representative postfire conditions. For this reason, the FERGI results are used at the watershed scale and represent a more extreme postfire erosion response than do the Cannon debris-flow model results. The limitations of the Cannon debris-flow model prevent it from distinguishing between moderate and high-intensity fires, which could lead to underestimating the impacts of wildfire and fuel treatments on erosion processes. Therefore, the hillslope sheet and rill erosion estimated by GeoWEPP plus the gully erosion-debris erosion estimated with FERGI represents the high end of the possible outcomes, while the sum of hillslope sheet and rill erosion from the GeoWEPP model plus the gully erosion-debris flow estimates from the Cannon model represents the likely low end. The Cannon model, however, uses a much higher rainfall intensity (25-year storm) than does the FERGI model (2.5-year storm used with gully volumes representative of a 10-year storm).[1] This disparity in storm design would likely increase the estimated volume of gully and debris-flow erosion from the Cannon model relative to the FERGI estimates, and compensate to some degree for any overestimation resulting from the limited gully volume information used with the FERGI results.

In sum, the results of the three different sediment models are not completely comparable because of the differing rainfall intensities used in the models, as well as other limitations. The model results used in this study should be considered estimates that are useful primarily for evaluating the effectiveness of fuel treatments in reducing postfire sediment.

To determine how sediment from the surface, gullies, and debris flows may affect water infrastructure, we compiled information on the extensive infrastructure network within the Mokelumne watershed, including reservoir capacity. For Tiger Creek Afterbay, there has been no updated information on its capacity since its construction in 1931, therefore we measured it with a bathymetric survey in 2013.

3.1 Analysis Focus Areas

The fire and sediment modeling efforts were conducted on the entire upper Mokelumne watershed. Appendices A-E discuss the model results in detail, while the discussion in this chapter is focused on the effects of fuel treatments on fire and sediment within three distinct areas (Table 3.1 and Figure 3.3). Descriptions and rationale for the selection of each is provided below:

- *Treated Analysis Units (TAU)*: All 41,000 hectare (ha) where fuel treatments were modeled within the treated (PostT) scenario (Figure 3.2). Chapter 2 details the selection process, the rational for the areas chosen for treatment, and how treatments were defined within the fire modeling. The impacts of modeled fuel treatments compared with the untreated results assume that all areas within the TAU boundary have been treated and continue to be maintained at that condition. While the non-contiguous nature of the TAU area makes it unlikely that any fire and sediment event would occur only within the TAU area, the

[1] A 25-year storm event is a rare and heavy precipitation event, the intensity of which is only expected roughly four times a century. A 10-year storm has an intensity that is expected every 10 years.

changes as a result of fuel treatments within the TAU indicate the upper end of the potential improvements under the modeled conditions.

- *Tiger Creek Afterbay Watershed (TCAB)*: This subwatershed is the undammed 39,000 ha catchment draining to the PG&E hydroelectric facility Tiger Creek Afterbay. TCAB was constructed in 1931 with a capacity of 4.8 million m^3 (Figure 3.3). Recent communications and preliminary capacity estimates suggest that the Tiger Creek Afterbay has lost 70% of its original capacity as a result of sedimentation. Through a bathymetric survey conducted in 2013, we were able to update our 2012 capacity estimate with a 2013 capacity estimate of approximately 1.2 million m^3 (Appendix F). This subwatershed was chosen in an effort to directly quantify the impact of fuel treatments in terms of potential avoided sediment generation and delivery to the Tiger Creek Afterbay. The fuel treatments included approximately 30% of the TCAB watershed, or 11,000 ha.

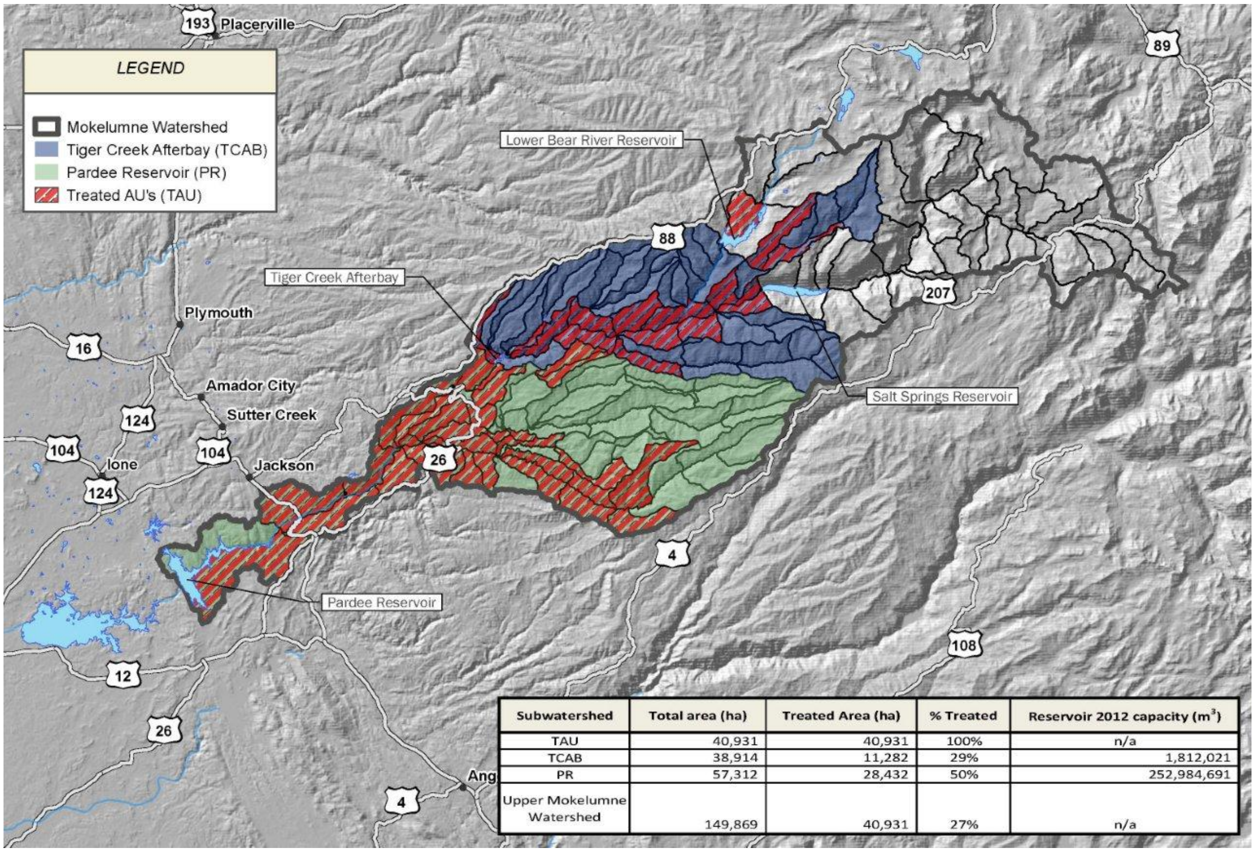
- *Pardee Reservoir Watershed (PR)*: The undammed 57,000 ha catchment draining to the East Bay Municipal Utility District water supply reservoir (Figure 3.3). This catchment includes all lands downstream of the TCAB, and while some fraction of sediment delivered to TCAB does make it downstream of the dam via a sluce valve, the separation of these two areas is assumed to provide a more realistic assessment of the subwatershed scale effects of fuel treatments. Pardee Reservoir was constructed in 1929 with a capacity of 259 million m^3; the 1995 capacity is estimated to be approximately 244 million m^3. In our modeled treatment scenario, fuel treatments covered approximately 50% of the PR watershed, or 28,000 ha.

Table 3.1: Subwatersheds analyzed and the treated area (hectares)

Subwatershed	*Total Area*	*Area Treated*	*Percent Treated*
Treated Area Units (TAU)	40,931	40,931	100%
Tiger Creek Afterbay (TCAB)	38,914	11,282	29%
Pardee Reservoir (PR)	57,312	28,432	59%

As Figure 3.3 illustrates, these three areas compose 65% of the upper Mokelumne watershed. The majority of the catchments for Lower Bear Reservoir and Salt Springs Reservoir are within a designated wilderness area, which restricts management options, so most of those areas were not included in this analysis. In addition, a large portion of these catchments is at high elevation, above the treeline, with very low burn probabilities. Given the objective of quantifying the effects of fuel treatments, these higher elevation lands were not included in the analyses. However, all maps communicating watershed scale modeling results do include these higher elevation areas.

Figure 3.3: Delineation of the subwatersheds analyzed to quantify the effect of fuel treatments



Subwatershed	Total area (ha)	Treated Area (ha)	% Treated	Reservoir 2012 capacity (m^3)
TAU	40,931	40,931	100%	n/a
TCAB	38,914	11,282	29%	1,812,021
PR	57,312	28,432	50%	252,984,691
Upper Mokelumne Watershed	149,869	40,931	27%	n/a

3.2 Key Models

Each of the models was developed, calibrated, and run by experts in the field. Summaries of the purpose, main inputs, and key outputs of each model are provided below. Detailed technical summaries of the specific platforms, inputs, limitations, and methods are provided in the respective appendices.

3.2.1 Fire behavior

Two geospatial fire modeling systems – Fire SIMulation system (FSim) and FlamMap5 – were used to quantify wildfire risk in the Mokelumne watershed and surrounding landscape in both a baseline and a hypothetical treatment scenario. Appendix A contains the details of the fire behavior modeling inputs, assumptions, outputs, and mapped results.

FSim (Finney et al. 2011) is a large-fire simulation model that simulates wildfire ignition, fire growth, and suppression using historical weather patterns, current fuel and vegetation, and topographic variables such as aspect and slope. The vegetation data were drawn from the LANDFIRE dataset and modified by the fire modeling team based on on-the-ground observations that conflicted with the original dataset. The model was run for 40,000 fire seasons to estimate burn probability and fire intensity for each 90 m pixel (or 0.81 ha) within the upper Mokelumne watershed (Figure 3.1) and the area surrounding it. FSim produces an estimate of current-year burn probability as all 40,000 modeled fire seasons represent the conditions of the current fire season. The only differences in the 40,000 fire seasons are the weather patterns (varied based on local weather data) and ignition points. In FSim, a wildfire grows until it is contained, either through suppression or self-extinguishment. Burn probability (BP) is the number of simulated large fires that burned each pixel, divided by the total number of simulated fire seasons (40,000). The fire modeling landscape (e.g., vegetation parameters) does not change between iterations, so FSim cannot be used to estimate future burn probability. In addition to the per 90 m pixel results described above, FSim also records the final burn perimeter of each simulated fire as a polygon, which we used to assess the distribution of burned area within the watershed.

Key inputs to FSim are climate, historical ignitions, fuel and vegetation, aspect, and slope. Historical local climatic records were used to represent daily climatic conditions over a fire season and to calculate the Energy Release Component (ERC), which is a key driver of FSim's fire probability and growth model. For the purposes of this analysis, we modeled at an ERC of roughly 85%, which represents bad conditions, but not as bad as the conditions under which the Power Fire burned in 2004. Historical fire ignition locations (both natural and human-caused) were used to create a map of relative ignition density.

FlamMap5 is a spatial fire behavior model that computes potential fire behavior characteristics such as rate of spread, flame length, and fireline intensity for every 30 m pixel over the entire study area under constant weather and fuel moisture conditions (Finney 2006). Fire severity in this modeling environment is related to flame length, the exact definition for which was decided within our team. For our purposes, we determined that all flames longer than 8 ft would lead to high severity impacts (summarized in Table 3.). FSim was used to calculate the probability that a pixel would burn and FlamMap5 was used to calculate the potential fire behavior for each burned pixel. The outputs from FlamMap5 were used as inputs for models describing soil erosion, such as GeoWEPP (described below) and the Canon and others (2010) debris flow model.

The same inputs used by FSim were used for the FlamMap5 runs. All model parameters for both FSim and FlamMap5 were held constant between the baseline and the treatment scenarios, except for the fuel and canopy characteristics that represented fuel treatments.

Table 3.2 Fire severity translation using pixel scale FlamMap5 flame length results

Fire severity rating	*Flame length (ft)*
None/unburnable	0
Low	0 > 4
Moderate	4 > 8
High	> 8

3.2.2 Surface erosion

A burned landscape becomes susceptible to erosion because of increased exposure to the elements and decreased cohesion as a result of destroyed vegetation, debris/litter layer, and root loss. GeoWEPP was used to model surface erosion rates of small-diameter (< 2 mm) hillslope sediments for both no-fire and postfire occurrence in the watershed. GeoWEPP is a geospatial update to the Water Erosion Prediction Project (WEPP) model. WEPP is a physically based model that considers local climate, hillslope and watershed topography, vegetation, and soil conditions, focusing on the hillslope erosion of very small soil components. The geospatial component of the Geo addition to WEPP enhances the results by allowing spatially explicit erosion rates per location. Key inputs to GeoWEPP are vegetation, aspect, slope length, steepness, and climate.

GeoWEPP scenarios included surface erosion estimates for existing, prefuel treatments (PreT) vegetation conditions (as of 2008) and posttreatments (PostT), both with and without the occurrence of fire. The GeoWEPP modeling team used the vegetation conditions developed by the fire modeling team. Fire severity for both PreT and PostT conditions were used as inputs to GeoWEPP per Table 3. from the FlamMap5 outputs. All postfire erosion results are based on each pixel burning and represent the erosion amount for the first year post fire (because of vegetation regrowth, second year erosion amounts for this sediment type are expected to diminish by 80%). The modeling team generated 50 years of climate based on historical precipitation and temperature datasets from local weather stations, and ran every hillslope polygon in the basin for 50 years to predict an average annual surface erosion loss expressed as mass of sediment per unit hillslope area for a single year (Mg/ha/yr). As such, the results reflect expected erosion during an average water year. An average sediment density of 1.5 Mg/m^3 was used to translate all GeoWEPP estimates in volumetric units of m^3 to simplify comparisons to existing reservoir capacities and typical sediment extraction, transport, and disposal estimates. The detailed methods and findings reported by the GeoWEPP modeling team are presented in Appendix C.

3.2.3 Gully erosion and debris flows

In addition to surface erosion, gullies and landslides (in this case, debris flows) can form post fire when surface water runs off unchecked by fire-killed vegetation. Evidence of current and historic landslides and gullies throughout the Mokelumne watershed comes primarily from aerial photos and field observations. However, there is not a comprehensive inventory of them and the cause of a particular landslide or gully is often not determined. To account for the large sediment movement and the hazard these events pose, we used two different models to help describe the formation and size of gullies and debris flows.

3.2.3.1 FERGI model

In recently burned areas, the vegetation often no longer acts as a barrier to surface water flow and the soils can become hydrophobic, the combination of which can create drainage lines. These drainage lines can erode upstream and banks can slump off, increasing the channel size and forming a gully. As gullies grow, they contribute more sediment and can be difficult to repair. The Fire-Enhanced Runoff and Gully Initiation model (FERGI) estimates the location and sizes of gullies that might form in the Mokelumne watershed after the modeled wildfires. FERGI estimates the postfire probability of runoff generation and gully initiation on hillslopes under both the PreT and PostT scenarios. Results include the return intervals for runoff rates and totals, and the upslope extent of gully formation (see Appendix E for more details).

FERGI model inputs are soil characteristics, slope, weather, and average hillslope length. The precipitation produced by the model replicates a 2.5-year storm (i.e., a storm intensity that is expected to occur once every 2.5 years, which is considered an average storm event) and is applied to the hillslope characteristics after a fire, when the soils have a water-repellant layer. Precipitation that is not absorbed and stored in the soil is considered by the model to be runoff that is routed downhill. FERGI estimates the number of 30 m^2 pixels within the study area that experience erosion during a 2.5-year storm. Field observations of two gullies that formed after the Power Fire of 2004 were applied to the model results to estimate the volume of sediment expected from each pixel. The storm that initiated the observed gullies in late December 2005 was approximately a 10-year 24-hour storm, as opposed to the 2.5-year storm used in the FERGI model.[2] Therefore, the gully dimensions measured in the field likely overestimate the dimensions of gullies generated by a storm of the intensity and duration used in the FERGI model. For these results, the modelers assume a gully shape of a rectangle with an average cross-section gully area of 5.9 m^2 multiplied by the 30-m width of the pixel to arrive at an average gully volume of 176 m^3. The watershed-wide results for both PreT and PostT are shown in Table 3.3. As mentioned previously, until we have more recorded gullies to refine our estimates, these volumes should be considered a worst-case scenario.

3.2.3.2 Cannon model

Similar to hillslope and gully erosion, the occurrence and size of debris flows increase during high-severity and/or long-duration rain events on recently burned landscapes. The Cannon postfire debris flow model results were created using empirical algorithms developed by Cannon and others (2010). These empirical algorithms were used to estimate the mean volume of debris flows at subwatershed outlets. In addition, the modeling team evaluated the probability of debris flow occurrence under a range of storm magnitudes and intensities.

Flame length, and its associated fire severity, was an input to the debris flow model, as were storm characteristics based on online NOAA data. This model was not run under unburned conditions and all of the debris flow predictions are for the year following a fire. However, the debris flow model and its results do not distinguish between moderate and high-severity fire. The detailed results of all storm iterations are presented in Appendix D. The modeled fuel treatments reduces the area of high- and moderate-severity fire, which reduces the likelihood and magnitude of the debris flow for all storm conditions reviewed, with the most treatment benefits realized under the circumstances of a 25-year 2-hour storm event.[3] The sediment experts on our team suggested that if

[2] A 10-year 24-hour storm has an intensity that is expected every 10 years, with rainfall occurring over 24 hours.

[3] A 25-year storm event is a rare and heavy precipitation event, the intensity of which is only expected roughly four times a century. A 2-hour event means that the rainfall occurs very intensely over a short period of time, as opposed to over a day or two.

the model were able to distinguish between high- and moderate-severity fire, the benefits of treatments on preventing debris flows would likely be more pronounced.

The Cannon model may underestimate both the volumes and impacts of the treatments, and could therefore be considered the low end of the sediment range, compared with the high end represented by the FERGI model. Because the Cannon model outputs spatially explicit volumes and as the model likely represents the lower range of potential outcomes, we only use the Cannon model results in the economic discussions below. However, as the reader reviews the economic discussions, it is important to keep in mind the FERGI results and the extent to which they could affect the outcomes of this study.

For reference, Table 3.compares the erosion results between the two models at three levels: the Treated Area Units, Tiger Creek Afterbay (TCAB) watershed, and Pardee Reservoir (PR) watershed. For each, we also describe the factor by which the FERGI model volumes are higher than the debris flow model volumes.

Table 3.3: The range of erosion results and the effectiveness of treatments that are possible based on the models

Treated area units	*Pretreatment*	*Posttreatment*	*Change*
Gully erosion (m^3)	6,373,427	1,837,333	71%
Debris flows (25 yr/2 hr) (m^3)	2,669,525	2,108,263	21%
Amount FERGI results are higher than debris	2.4 times	0.9 times	
Tiger Creek Afterbay	*Pretreatment*	*Posttreatment*	*Change*
Gully erosion (m^3)	10,378,460	6,903,250	33%
Debris flows (25 yr/2 hr) (m^3)	2,488,468	2,207,787	11%
Amount FERGI results are higher than debris	4.2 times	3.1 times	
Pardee Reservoir	*Pretreatment*	*Posttreatment*	*Change*
Gully erosion (m^3)	15,265,767	6,325,903	59%
Debris flows (25 yr/2 hr) (m^3)	3,267,206	2,942,310	10%
Amount FERGI results are higher than debris	4.7 times	2.1 times	

3.3 Quantification of Fuel Treatments Effects

The model results were used to estimate the effects of fuel treatments on fire behavior and postfire impacts using three different analysis techniques.

- **Landscape analyses:** FSim, FlamMap5, GeoWEPP, and the debris flow models were used to capture the diverse terrain of the upper Mokelumne watershed. The models produced outputs at 30 m and 90 m pixel size, which created approximately 1.6 million data points that represent fire and sediment behavior across the entire watershed. A series of meaningful metrics was chosen to represent the results of each of these four models, so that we could better communicate the implications of fuel treatments on fire and erosion behavior. The definitions and methods used to create each of the raster distribution metrics are presented in Table 3.4. The landscape analysis results are presented for each of the subwatersheds and include the PreT and PostT values, as well as the change as a result of treatment.

  For each subwatershed, selected datasets were tested to verify that the populations of the raster metric values were statistically different before and after treatment, thus providing confidence that the modeled treatment scenario would be statistically effective at changing fire and sediment conditions on the landscape. To test statistical confidence, 1,000 pixels were randomly resampled from the raster datasets 10,000 times using a bootstrapping technique to test our confidence of the actual difference between the PreT and PostT datasets. The results are presented graphically to provide additional visual evidence of how fuel treatments are predicted to change specific fire and sedimentation rates within each subwatershed (Figure 3.7).

  A series of relative difference maps (Figures 3.4-3.6; 3.8-3.11) display the distribution and magnitude of fire and sediment changes throughout the upper Mokelumne watershed as a result of fuel treatments. Each relative percent reduction map was created by subtracting the PostT from the PreT values for each pixel and dividing by the PreT value. For the metrics mapped, any increases in pixel values were attributed to modeling error and are not displayed or discussed in this chapter.

- **Fire-specific analyses:** The 40,000-fire season simulations run through the FSim model result in a set of specific fire boundaries across the landscape that can be viewed and analyzed individually. Data associated with each fire include its start location, total burn area, and final perimeter. The FSim fire perimeters were combined with the GeoWEPP erosion estimates post fire for both PreT and PostT, allowing us to calculate the total burn area and total sediment erosion for each fire modeled by FSim. Given that FSim does not accurately simulate small fires (e.g., those that burn less than 100 ha), our fire-specific analysis only includes simulated fires larger than 100 ha. The combination of the modeling data allows us to estimate the annual probability that fire of a given size or sediment erosion of a given volume will occur somewhere in the TCAB or PR watersheds. This allows us to compare the differences from fuel treatments in expected burn area and total sediment erosion for specific modeled fires in TCAB and PR fuel treatments.

- **30-year, Five Fire scenario (2013-2043):** Perhaps the greatest potential benefit to the human and environmental community of an effective fuel treatments program is the long-term reduced fire severity, and the associated reduction in sediment erosion events. In an effort to quantify these long-term effects, we developed a hypothetical fire occurrence scenario from present to 30 years into the future (2013-2043). This scenario was used to quantify the cumulative effects of fuel treatments on sediment erosion and delivery to two critical reservoirs: Tiger Creek Afterbay and Pardee Reservoir. The scenario incorporated projections of increased fire frequency and severity that are expected over the next 30 years, focusing on five specific fires within the upper Mokelumne watershed that were selected from the fire modeling data and that collectively burn 14% of the watershed under PreT conditions. The same ignitions and associated burn areas are compared PostT. These fire perimeters are also used to quantify a series of other avoided costs as a result of fuel treatments (See Chapters 4-9).

Table 3.4: Description, calculation, and source models for each metric used in raster distribution analysis

Metric	units	Description	Calculation	Source model
Burn probability (BP) is a direct output from the FSim fire behavior model.				
Mean BP	annual	mean probability that a fire will occur in any one pixel in a given year	sum of all pixel values / total number of pixels	FSim
50th percentile BP		50th percentile pixel BP	distribution analysis of pixel population	
90th percentile BP		90th percentile pixel BP		
Area with PreT 90th BP or higher	ha	total area with BP >= PreT 90th percentile Only 10% of the watershed area has a BP in the 90th percentile or higher.	count sum of pixels >= to value * pixel area (ha)	
Flame Length (FL) is direct output from the FSim and Flame Map fire behavior models.				
Mean flame length	ft	mean of all pixel flame lengths	sum of all pixel values / total number of pixels	FSim, FlamMap
50th percentile flame length		50th percentile pixel flame length	distribution analysis of pixel population	
Area with >= 8 ft flame length	ha	total area with flame length >= 8 ft		
*Fire Hazard Erosion hazard: A calculated output where fire hazard (FH) = flame length * fire BP for each pixel.*				
Mean fire hazard	ft	mean of all pixel fire hazard values	sum of all pixel values / total number of pixels	FSim, FlamMap
50th percentile fire hazard		50th percentile pixel fire hazard	distribution analysis of pixel population	
90th percentile fire hazard		90th percentile pixel fire hazard		
Area >= PreT 90th fire hazard	ha	total area with fire hazard >= PreT 90th percentile	count sum of pixels >= to value * pixel area (ha)	
Surface Erosion (SE): The predicted volume of sediment generated during the year post fire given average annual climatic conditions. Surface erosion is direct output from the GeoWepp model, that requires a fire severity from FlamMap flame length outputs as an input to estimate surface erosion.				
Mean annual surface erosion	m^3/ha/yr	mean of all pixel surface erosion	sum of all pixel values / total number of pixels	FlamMap, GeoWepp
50th percentile surface erosion		50th percentile pixel surface erosion	distribution analysis of pixel population	
90th percentile surface erosion		90th percentile pixel surface erosion		
Area >= PreT 90th surface erosion	ha	total area with burn probability >= PreT 90th percentile	count sum of pixels >= to value * pixel area (ha)	
*Surface erosion hazard: A calculated output where surface erosion hazard = surface erosion * fire BP for each pixel.*				
Mean erosion hazard	m^3/ha/yr	mean of all pixel erosion hazard	sum of all pixel values / total number of pixels	FSim, FlamMap, GeoWepp
50th percentile erosion hazard		50th percentile pixel erosion hazard	distribution analysis of pixel population	
90th percentile erosion hazard		90th percentile pixel erosion hazard		
Area >= PreT 90th erosion hazard	ha	total area with erosion hazard >= PreT 90th percentile	count sum of pixels >= to value * pixel area (ha)	
Debris flow volume: A direct output from the Debris Flow model that generates a predicted debris flow sediment volume given the occurrence of a 25yr 2hr intensity rainfall event within one year post fire.				
Total potential debris flow volume (25yr 2hr)	m^3	sum of mean of all debris flow volumes given the occurrence of a 25yr 2hr intensity rainfall event	sum of hillslope debris flow volumes with area of interest	Debris Flow
Potential range of total		sum of high and low debris flow volumes, respectively given the occurrence of a 24yr 2hr intensity rainfall event		
50th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	50th percentile of the mean debris flow volume for each individual hillslope	distribution analysis of hillslope debris flow volume population	
Potential range of 50th percentile		50th percentile of the low and high debris flow volumes, respectivly, for each individual hillslope		
90th percentile debris flow volume (25yr 2hr)		90th percentile of the mean debris flow volume for each individual hillslope		
Potential range of 90th percentile		90th percentile of the low and high debris flow volumes, respectivly, for each individual hillslope		

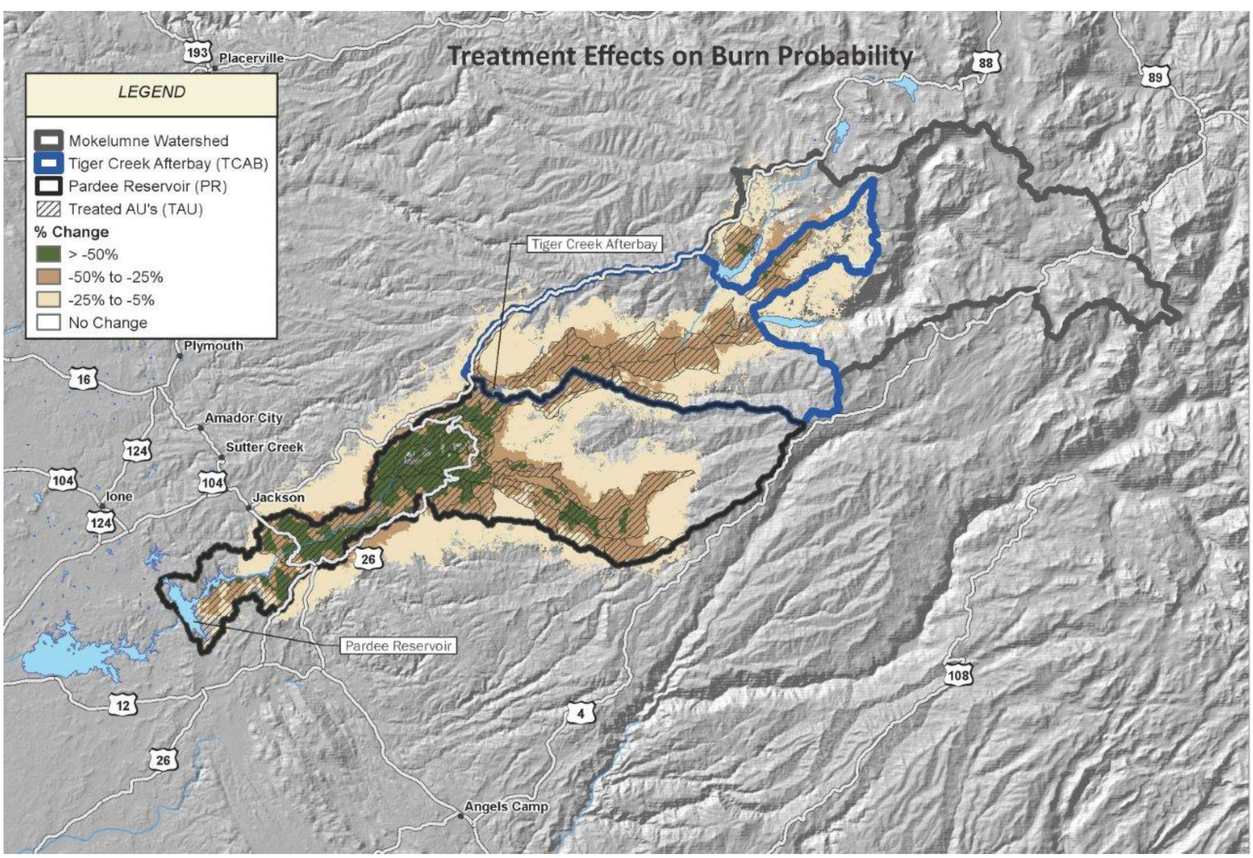
3.4 Landscape Analysis

3.4.1 Treated analysis units (TAU)

The effects of fuel treatments in the areas where fuel treatments were implemented in the models (TAU; Figure 3.2) were analyzed to quantify the potential effects of treating an entire area. As expected, the magnitude of change from treatment is the greatest for the TAU area, compared to TCAB and PR watersheds fuel treatments. The TAU polygon (Figure 3.2) is not an actual contiguous catchment, and only the landscape analysis was conducted.

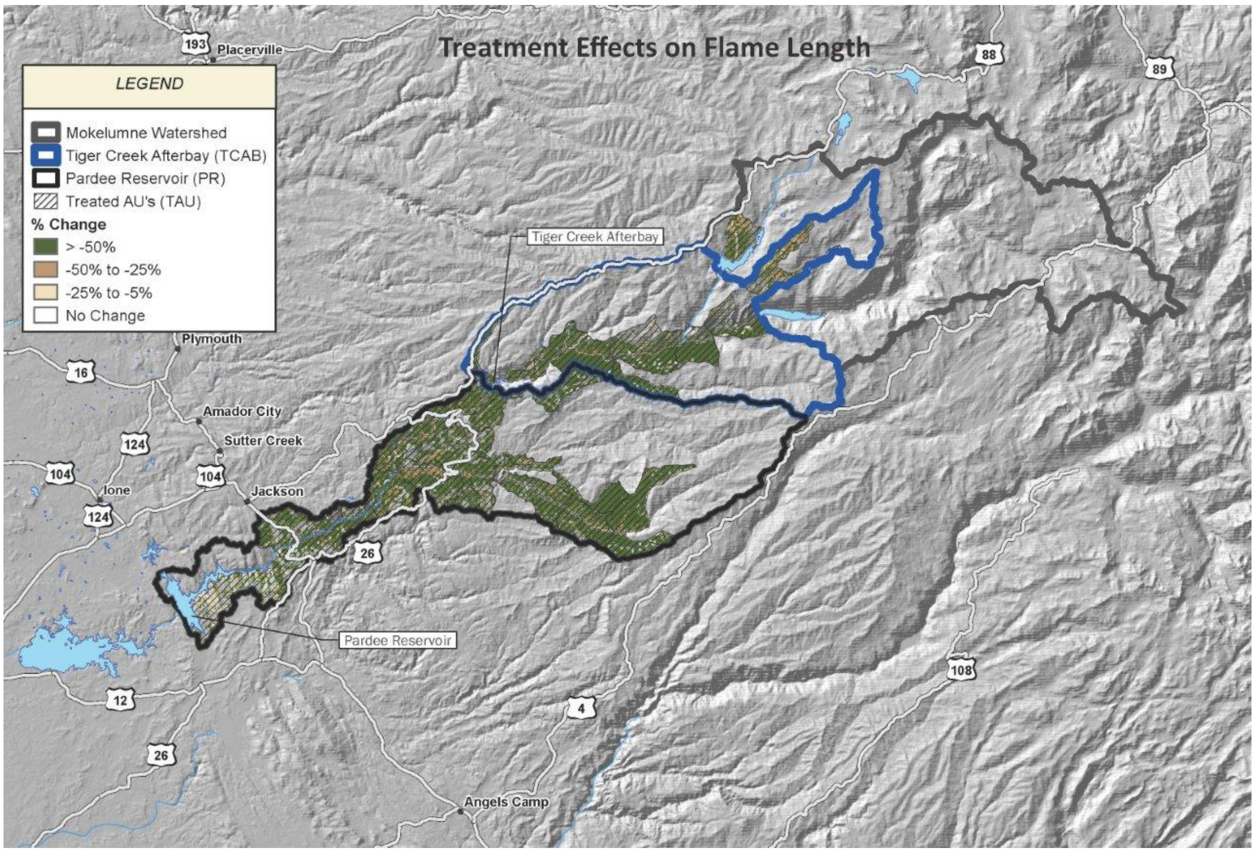
The comparisons of PreT and PostT fire behavior illustrate the significant effect fuel treatments can have on the likelihood and intensity of fire, as well as on the resulting erosion rates (Table 3.5). The 90th percentile burn probability, from the existing conditions (PreT) model, is 0.79%, which means that in any given year, 10% of the TAU area has a 1 in 126 chance of burning. Under current conditions, the amount of the TAU area that has an annual burn probability (BP) of at least 0.79% is 4,078 ha, or 10% of the TAU area. After fuel treatments were implemented in the model, the area with a BP greater than 0.79% was reduced by 61%, to just 1,601 ha. Figure 3.4 presents the relative change in the BPs, calculated as the (PostT BP- PreT BP)/PreT BP for the entire upper Mokelumne watershed. Notice that the greatest reductions in BP are within the TAU boundaries, but that fuel treatments do influence the burn probabilities of adjacent locations.

Figure 3.4: Relative change in pixel scale burn probability as a result of treatment



Fuel treatments also reduce the severity of simulated wildfires. The area expected to experience a high severity greater than 8-ft flame length was reduced from 16,857 ha in current conditions to 1,520 ha following treatment, a 91% reduction. As mapped in Figure 3.5, this difference in flame length suggests that treatments result in severity reductions on the lands on which they are implemented but not adjacent lands. This contrasts with the results for BP, where treated areas do positively impact the BP of adjacent lands.

Figure 3.5: Relative change in pixel scale flame length as a result of treatment



Fire hazard is calculated as the product of the annual BP and flame length, thereby identifying areas that have a combined high probability of catching fire and that are expected to burn at high severity. Treatment had a significant effect on the fire hazard within the TAU, reducing the area with a relatively high hazard value of 0.032 (90^{th} percentile existing conditions) from 4,095 ha to only 404 ha, a 90% reduction (Figure 3.6).

Figure 3.6: Relative change in pixel scale fire hazard as a result of treatment

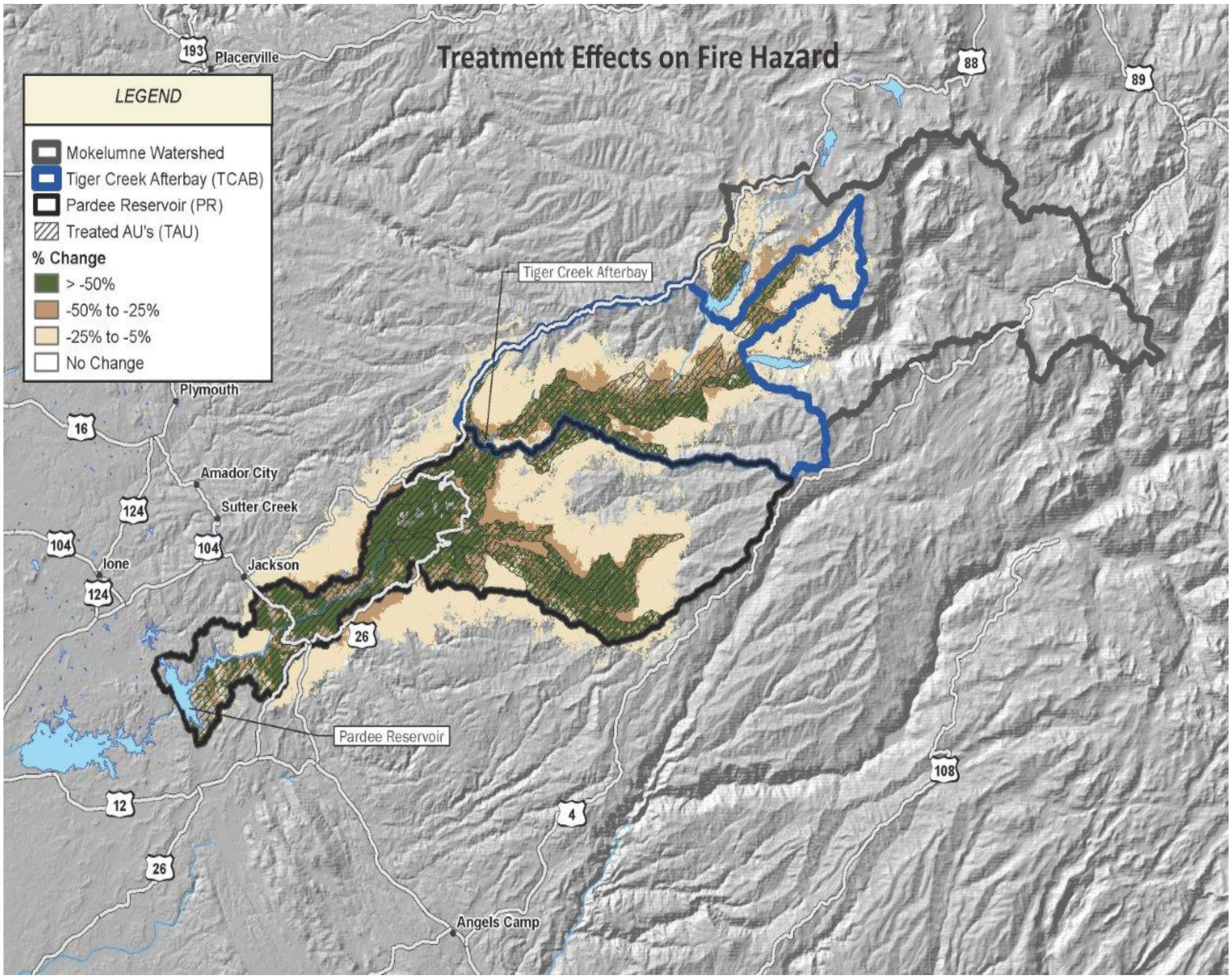
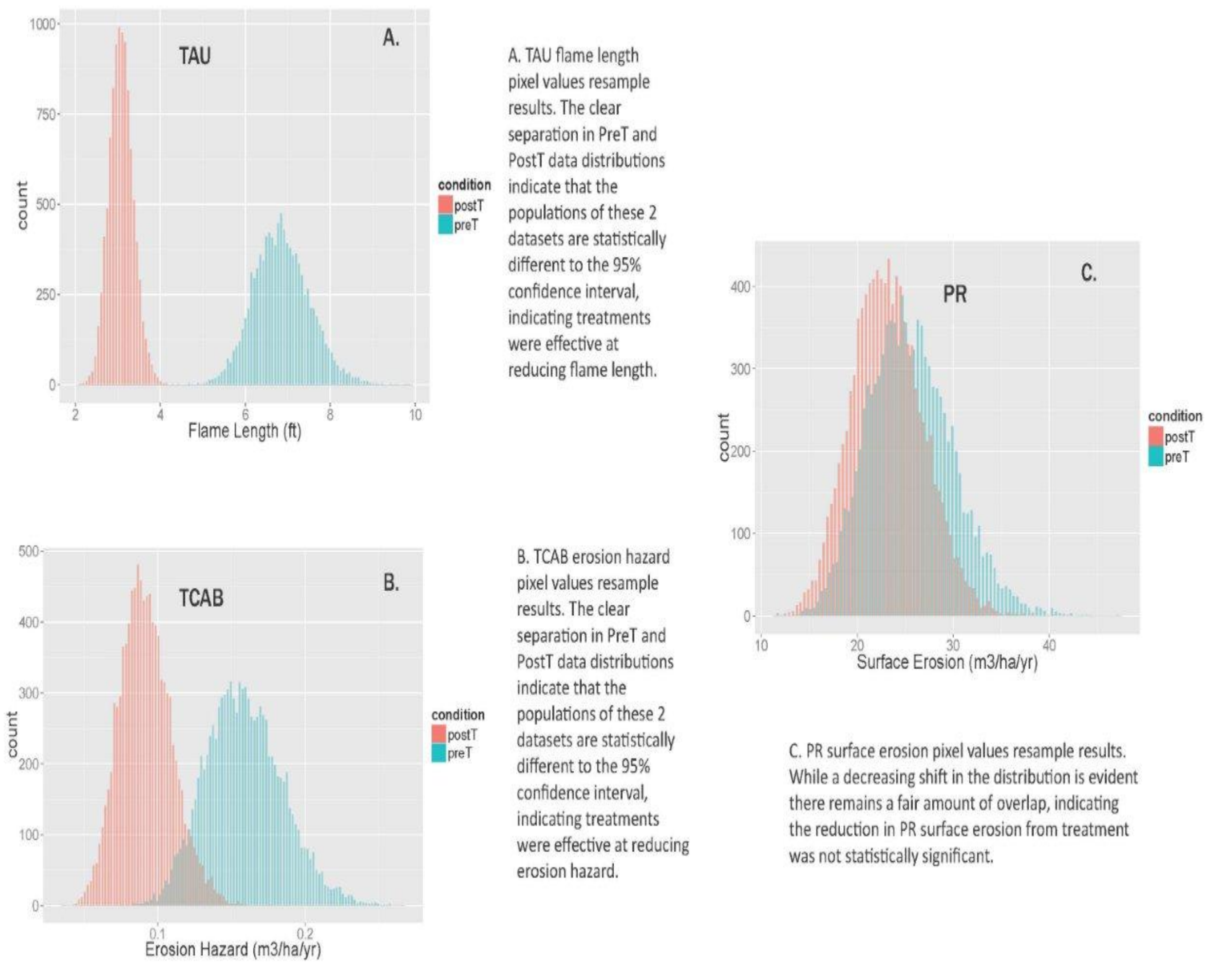


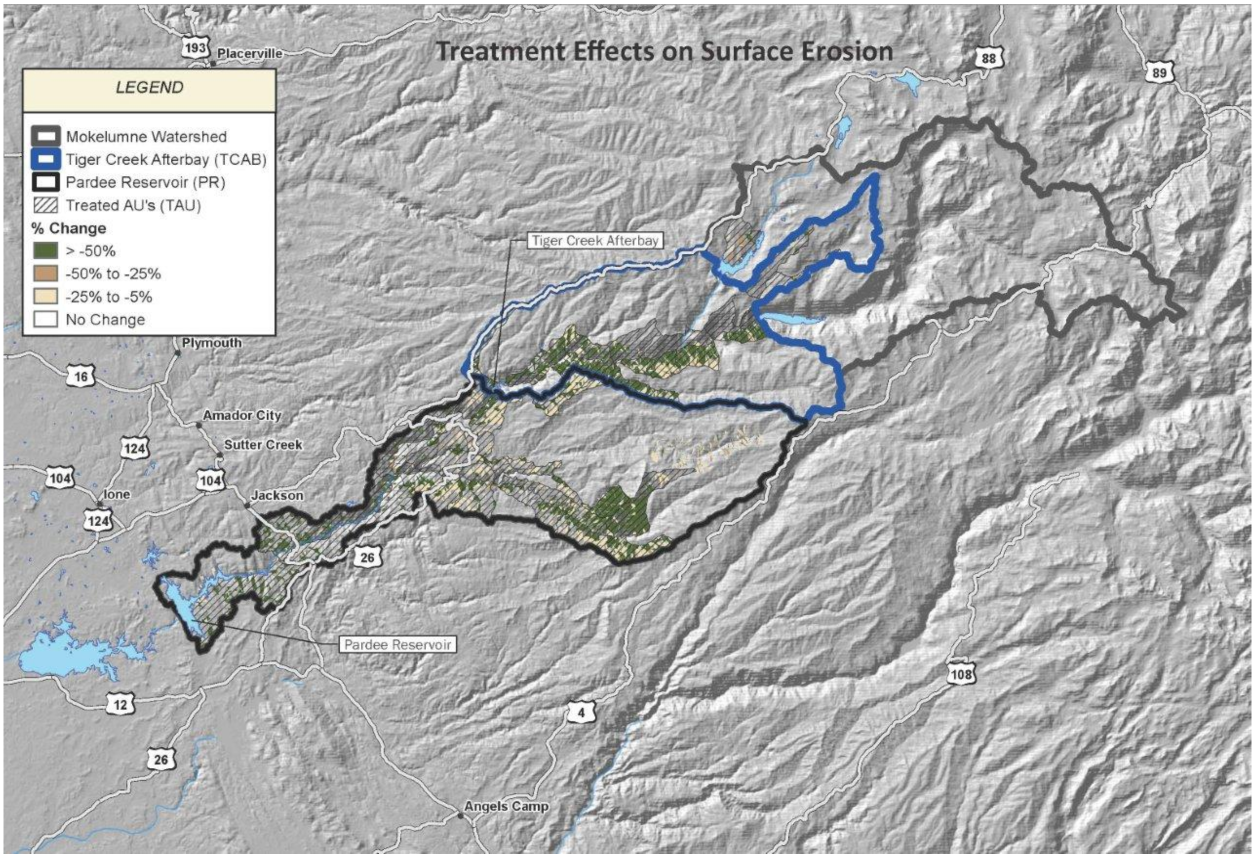
Figure 3.7, Graph A presents the results of the relative change in flame length from the TAU following statistical analysis. The data distribution of the flame length of both datasets and the clear separation of the distributions indicate that these datasets are statistically different at the 95% confidence interval. These results suggest fuel treatments will reduce mean flame length within the treatment areas from 6.6 ft to 3.2 ft.

Figure 3.7: Pixel value resampling results for select metrics



This reduction in flame length significantly lowered the surface erosion rates for the first year following a fire, with a mean reduction of 38% and with the amount of area where the surface erosion rate equals or exceeds the PreT 90th percentile reduced by 83%. Comparing the PreT and PostT surface erosion rates, the amount of area experiencing the PreT 90th percentile rate dropped by 53% in PostT. The percent change in surface erosion due to fuel treatments in the TAUs is illustrated in Figure 3.8.

Figure 3.8: Relative change in pixel scale surface erosion as a result of treatment



Surface erosion hazard reductions as a result of treatment are similar in magnitude, with a 92% reduction in the lands predicted to have both a high likelihood and a high severity of surface erosion. Figure 3.9 shows the relative distribution of the percent change between PreT and PostT erosion hazard. While the probability of a debris flow the first year post fire will vary, treatment reduces the predicted severity or volume amount of material mobilized by 21% under the conditions of a 25-year 2-hour storm event the first year post fire. Figure 3.10 presents the percent change due to treatments in debris flow volumes for each hectare for each hillslope for a 25-year 2-hour storm. Figure 3.11 summarizes the reduced probability of the debris flow happening from a 25-year 2-hour rain event.

Figure 3.9: Relative change in pixel scale surface erosion hazard as a result of treatment

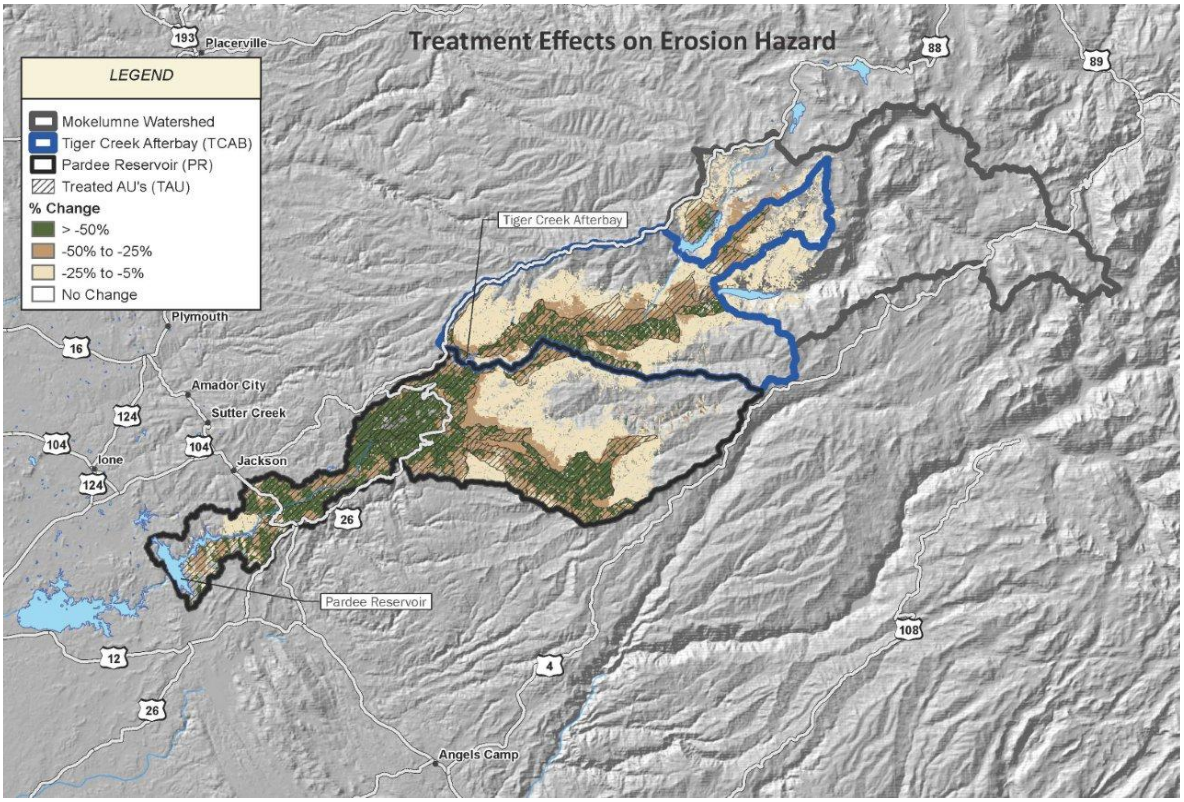


Figure 3.10: Relative change in debris flow volumes as a result of treatment (m^3/ha)

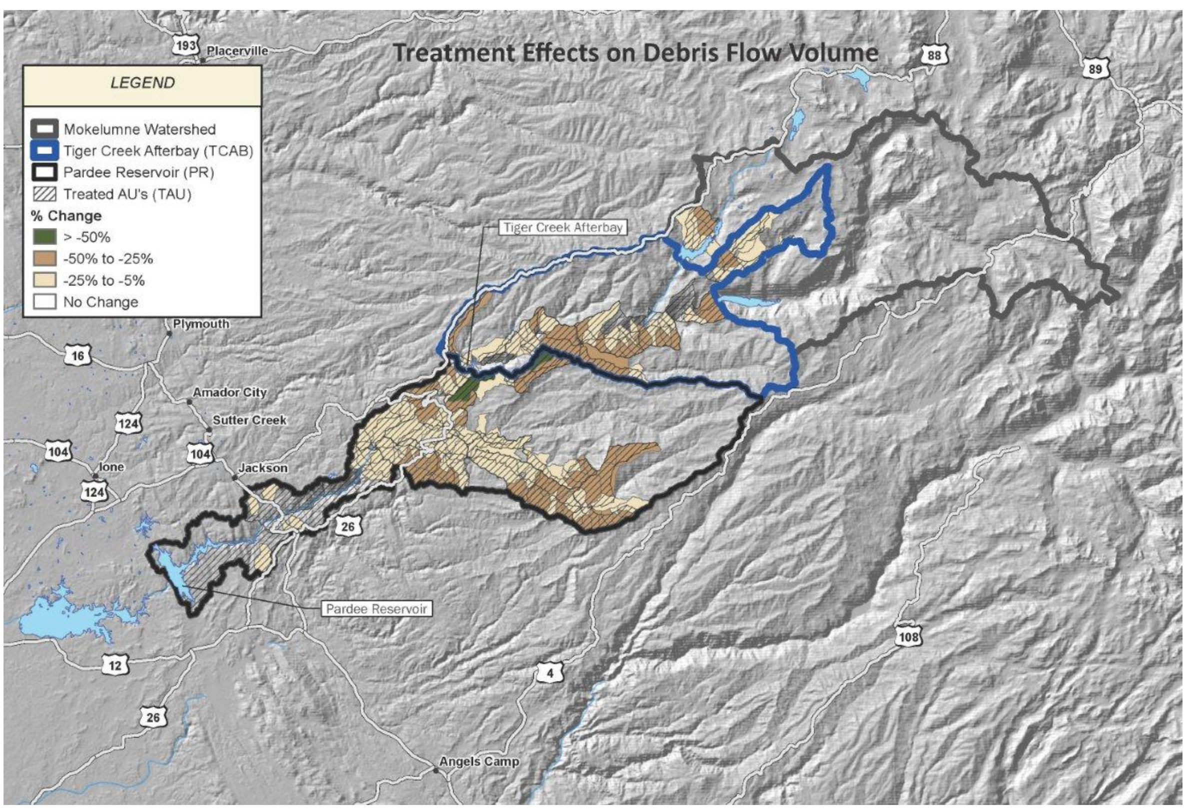


Figure 3.11: Relative change in debris flow probability as a result of treatment

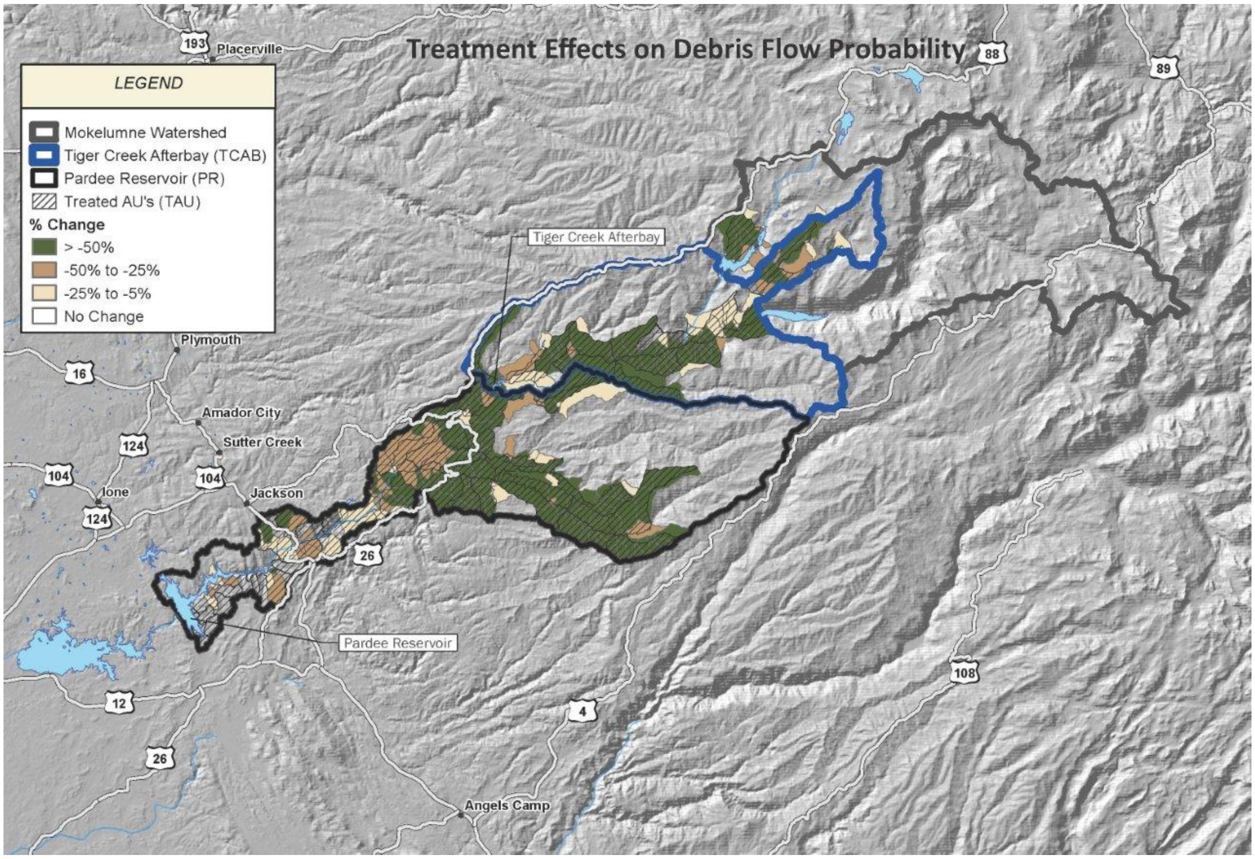


Table 3.5: Summary of key model results for PreT and PostT scenarios in the TAU

TREATED ANALYSIS UNITS (TAU)				
Metric	**units**	**PreT**	**PostT**	**change**
Mean BP	annual	0.50%	0.31%	-39%
50th percentile BP	annual	0.45%	0.26%	-42%
90th percentile BP	annual	0.79%	0.55%	-31%
Area with PreT 90th BP or higher	ha	4,078	1,601	-61%
Mean flame length	ft	6.6	3.2	-52%
50th percentile flame length	ft	5.7	2.5	-57%
Area with >= 8 ft flame length	ha	16,857	1,520	-91%
Mean fire hazard	ft	0.017	0.007	-59%
50th percentile fire hazard	ft	0.014	0.005	-67%
90th percentile fire hazard	ft	0.032	0.015	-55%
Area >= PreT 90th fire hazard	ha	4,095	404	-90%
Mean annual surface erosion	m^3/ha/yr	30.5	17.3	-38%
50th percentile surface erosion	m^3/ha/yr	12.3	10.1	-18%
90th percentile surface erosion	m^3/ha/yr	84.2	39.8	-53%
Area >= PreT 90th surface erosion	ha	3,734	633	-83%
Mean erosion hazard	m^3/ha/yr	0.158	0.050	-68%
50th percentile erosion hazard	m^3/ha/yr	0.060	0.026	-56%
90th percentile erosion hazard	m^3/ha/yr	0.432	0.143	-67%
Area >= PreT 90th erosion hazard	ha	3,734	289	-92%
Total potential debris flow volume (25yr 2hr)	m^3	2,669,545	2,108,263	-21%
Potential range of total	m^3	2,372,888 - 3,062,647	1,876,958 - 2,414,160	
50th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	64.4	55.0	-15%
Potential range of 50th percentile	m^3/ha/yr	58.0-73.5	49.2 - 63.1	
90th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	108.2	89.2	-18%
Potential range of 90th percentile	m^3/ha/yr	96.0 - 124.1	79.9 - 102.5	

3.4.2 Tiger Creek Afterbay (TCAB)

Table 3.6 presents the results of the landscape analysis for TCAB. While fuel treatments were modeled on less than 30% of the TCAB watershed (11,282 ha of 38,914 ha), the treatments resulted in significant reductions in the sediment erosion rates. The treatments are estimated to reduce the mean surface erosion rate from the full TCAB watershed from 24.3 to 19.2 m^3/ha/yr and the area with relatively severe erosion (90^{th} percentile PreT) by 36%. Furthermore, the mean surface erosion hazard is predicted to be more than 41% lower after treatment, a difference that is statistically significant at the 95% confidence interval (Figure 3.7, Graph B). The debris flow volume differences due to treatments were less substantial, with a 3% reduction in the median (50^{th} percentile) volume and a reduction in the total potential debris flow of 220,000 m^3 of material, which amounts to a change of only 11% from the pretreatment estimates.

Table 3.6: Summary of key model results for PreT and PostT scenarios in the TCAB

Landscape Analysis Results

TIGER CREEK AFTERBAY WATERSHED (TCAB)				
Metric	**units**	**PreT**	**PostT**	**change**
Mean BP	annual	0.38%	0.32%	-16%
50th percentile BP	annual	0.38%	0.30%	-20%
90th percentile BP	annual	0.53%	0.49%	-7%
Area with PreT 90th BP or higher	ha	3,823	2,568	-33%
Mean flame length	ft	5.3	4.2	-20%
50th percentile flame length	ft	3.7	2.6	-31%
Area with >= 8 ft flame length	ha	8,268	5,367	-35%
Mean fire hazard	ft	0.011	0.008	-26%
50th percentile fire hazard	ft	0.009	0.006	-38%
90th percentile fire hazard	ft	0.023	0.017	-24%
Area >= PreT 90th fire hazard	ha	3,846	1,345	-65%
Mean annual surface erosion	m^3/ha/yr	24.3	19.2	-21%
50th percentile surface erosion	m^3/ha/yr	7.9	7.3	-7%
90th percentile surface erosion	m^3/ha/yr	64.5	49.8	-23%
Area >= PreT 90th surface erosion	ha	3,622	2,321	-36%
Mean erosion hazard	m^3/ha/yr	0.086	0.051	-41%
50th percentile erosion hazard	m^3/ha/yr	0.024	0.019	-18%
90th percentile erosion hazard	m^3/ha/yr	0.24	0.14	-44%
Area >= PreT 90th erosion hazard	ha	3,622	1,422	-61%
Total potential debris flow volume (25yr 2hr)	m^3	2,488,468	2,207,787	-11%
Potential range of total	m^3	2,181,817 - 2,901,763	1,935,652 - 2,574,581	
50th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	62.0	60.0	-3%
Potential range of 50th percentile	m^3/ha/yr	54.2 -72.6	52.5-69.7	
90th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	101.9	94.4	-7%
Potential range of 90th percentile	m^3/ha/yr	89.4 - 118.4	83.12 - 109.6	

3.4.3 Pardee Reservoir (PR)

The fuel treatments were applied to approximately 50% of the PR subwatershed (28,432 ha of the 57,312 ha watershed). The median probability that a given area would burn was reduced by 22%, while the areas with 90th percentile BPs (PreT) were reduced by 53% (Table 3.7). The area expected to experience a high severity fire (greater than 8-ft flame length) was reduced from 12,459 to 6,525 ha, a 48% reduction. The mean annual surface erosion rate was reduced from 25.0 to 19.2 m^3/ha/yr. The treatments are predicted to reduce the total area with severe erosion hazard (90th percentile PreT) by 82%, from 2,609 to 482 ha. The median debris flow volume generated during a 25-year 2-hour storm decreased by 24%. Both the surface erosion and debris flow magnitudes are predicted to be lower as a result of fuel treatments, an effect that would provide a tremendous benefit to the local upland and aquatic ecosystems given the deleterious effects of wide spread postfire erosion.

Table 3.7: Summary of key model results for PreT and PostT scenarios in the PR

Landscape Analysis Results

PARDEE RESERVOIR WATERSHED (PR)				
Metric	**units**	**PreT**	**PostT**	**change**
Mean BP	annual	0.52%	0.38%	-26%
50th percentile BP	annual	0.47%	0.37%	-22%
90th percentile BP	annual	0.75%	0.60%	-20%
Area with PreT 90th BP or higher	ha	5,727	2,701	-53%
Mean flame length	ft	6.2	4.5	-27%
50th percentile flame length	ft	5.9	3.4	-42%
Area with >= 8 ft flame length	ha	12,459	6,525	-48%
Mean fire hazard	ft	0.012	0.009	-27%
50th percentile fire hazard	ft	0.009	0.006	-38%
90th percentile fire hazard	ft	0.026	0.020	-22%
Area >= PreT 90th fire hazard	ha	14,840	7,249	-51%
Mean annual surface erosion	m^3/ha/yr	25.0	19.2	-23%
50th percentile surface erosion	m^3/ha/yr	9.5	8.7	-8%
90th percentile surface erosion	m^3/ha/yr	69.4	45.1	-35%
Area >= PreT 90th surface erosion	ha	5,216	2,765	-47%
Mean erosion hazard	m^3/ha/yr	0.135	0.074	-45%
50th percentile erosion hazard	m^3/ha/yr	0.046	0.028	-40%
90th percentile erosion hazard	m^3/ha/yr	0.37	0.19	-49%
Area >= PreT 90th erosion hazard	ha	2,609	482	-82%
Total potential debris flow volume (25yr 2hr)	m^3	3,267,206	2,942,310	-10%
Potential range of total	m^3	1,545,681 - 1,961,087	2,615,501- 3,374,901	
50th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	69.0	52.1	-24%
Potential range of 50th percentile	m^3/ha/yr	50.8 - 64.7	45.8 - 55.8	
90th percentile debris flow volume (25yr 2hr)	m^3/ha/yr	98.3	91.5	-7%
Potential range of 90th percentile	m^3/ha/yr	88.1 - 111.6	80.2 - 105.2	

3.5 Fire-Specific Analysis

The fire perimeter results from FSim were combined with the GeoWEPP surface erosion results to determine the expected sediment generation for each simulated fire that occurred over the 40,000 simulated fire seasons. The fire perimeter sediment effects were clipped for the two watersheds of interest (TCAB and PR) and the series of metrics below were quantified to communicate the effects of fuel treatments on burn area and associated sediment erosion. Only simulated fires 100 ha and greater were included in the analyses because FSim is most accurate when modeling fires of this size. The results are discussed below and detailed in Figures 3.12 and 3.13. Term definitions are as follows:

- *Watershed BP* is the estimated annual likelihood that a fire over 100 ha will reach some part of the watershed (decimal fraction). A burn probability of 0.4%, equates to a 1 in 250 chance of burning in a single year.
- *Conditional burn area* is the mean watershed area burned in a single fire season.
- *Expected area burned* is an estimate of the mean annual watershed area burned across all fire seasons.
- *Max area burned* is the largest area burned in any single fire season.
- *Percentile burn area* is the size of fire that represents both the median (50th) and 90th percentile (less frequent larger events) given the distribution of simulated fires of 100 ha or greater in size.

- *Conditional surface erosion* is the estimated mean sediment produced in a single fire season, given that a fire >100 ha occurs within the watershed boundary.
- *Expected annual surface erosion* is an estimate of the mean annual fire-induced sediment production for fires >100 ha, given the 40,000 years of simulation. This does not include sediment produced without wildfire.
- *Expected surface erosion avoided* is the difference between PreT and PostT expected annual sediment production, providing a simple measure for the overall effectiveness of the treatments at reducing sediment.
- *Max sediment* is the largest amount of sediment produced in the watershed in any fire season.
- *Percentile surface erosion* is the volume of sediment from surface erosion that represents both the median (50th) and 90th percentile.

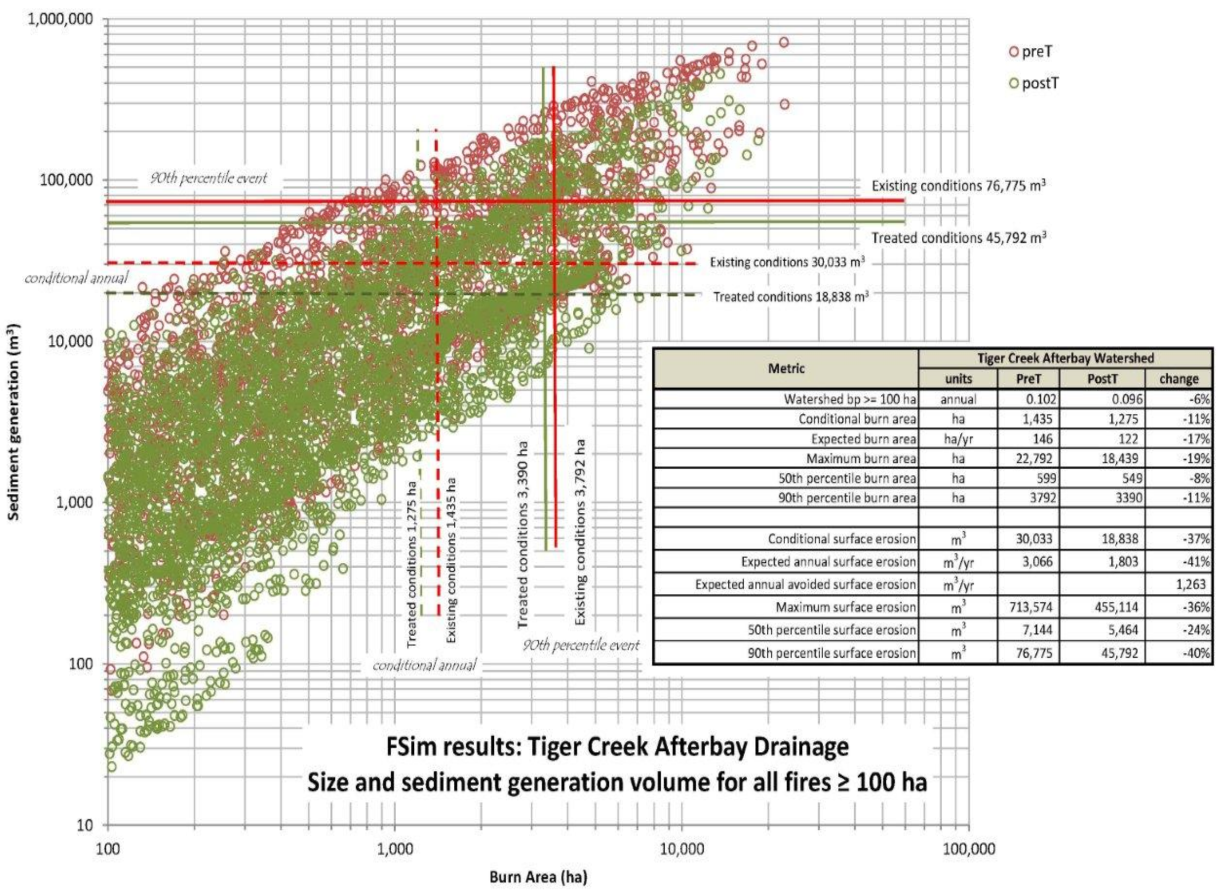
3.5.1 Tiger Creek Afterbay (TCAB)

Based on the current watershed conditions, there is a 10% chance each year that a fire 100 ha or larger will occur within the TCAB watershed; the modeled treatments reduced this annual likelihood to 9.6%. The individual fire results are presented graphically in Figure 3.12. Each point on Figure 3.12 represents the burn area and volume of sediment erosion for each fire simulated in the TCAB watershed for both PreT and PostT conditions. The visual reduction in sediment erosion PostT is discernible in the graphic and supported by the metrics included in the table.

While the likelihood of large fires occurring is only slightly reduced as a result of treatment, the size of the fires and their associated erosion are significantly lower due to reductions in fire severity. Given that each fire perimeter is a distinct location with, among other characteristics, unique aspect, soils, slope, and burn severity, there is a broad range of predicted sediment erosion from the hundreds of simulated fires. Thus, the location of a fire within the subwatershed has a large impact on the amount of erosion it is likely to produce.

Regardless of the location of the fires within TCAB, fuel treatments are expected to reduce annualized sediment erosion by just under half (1,260 m^3, or 41%). For context, the average Olympic-sized pool can hold 2,500 m^3. Over long time periods, this annualized savings can be significant, but the single-year pulse of large amounts of sediment in the year following a fire has the potential to be much more destructive than the annualized volumes indicate. Examples of the volumes expected following a single fire are discussed in more detail in section 3.6.2. In general, the implementation of the fuel treatments is predicted to reduce surface erosion for large fires by 30-40% from 2008 vegetation conditions.

Figure 3.12: Sediment generation compared with burn area, with each dot representing a modeled fire in TCAB (red = pretreatment fire, green = posttreatment fire)

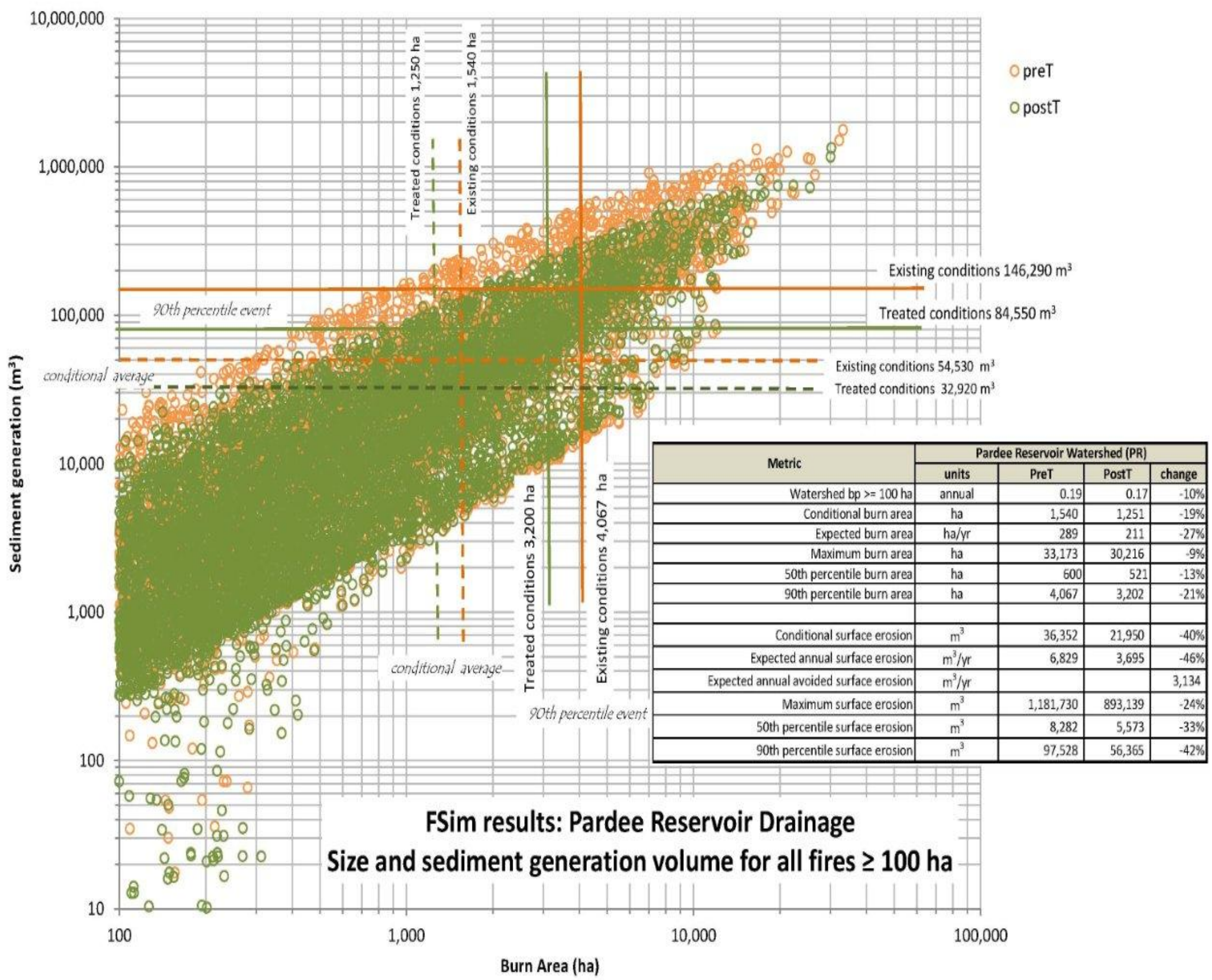


3.5.2 Pardee Reservoir (PR)

Under the current conditions, on average there is a 19% chance each year that a fire larger than 100 ha will burn somewhere in the PR watershed, as delineated in this analysis (Figure 3.3). The proposed fuel treatments reduced this likelihood to 17%. Additionally, the 90th percentile PreT fire area (4,067 ha) was reduced to 3,202 ha in size. In Figure 3.13, the points represent the burn area and sediment erosion volume for each fire simulated in the Pardee watershed for both PreT and PostT conditions. The data in Figure 3.13 highlight the change in burned area and surface erosion due to treatments.

Despite the relatively small decrease in the likelihood that a large fire will occur after fuel treatments, both the amount of erosion and the total burned area from the fires are significantly lower, largely as a result of decreased burn severity. As discussed above, in the TCAB the location of a fire's burn perimeter within the watershed plays a large role in determining the cumulative impacts of the fire. The same holds true for PR. Given the annual probability of a fire greater than 100 ha and the conditional surface erosion, expected annualized avoided surface sediment is 3,130 m^3, a reduction of almost 50% annually. Over time, this savings can be substantial. Overall, the implementation of the fuel treatments scenario is predicted to reduce surface erosion from large fires by 25-42%.

Figure 3.13: Sediment generation compared with burn area, with each dot representing a modeled fire in PR (orange = pretreatment fire, green = posttreatment fire)



3.6 The Hypothetical Next 30 Years of Fire (2013-2043)

We designed a 30-year fire scenario to quantify the potential long-term effects of the defined and modeled fuel treatments program. The general process to create the scenario and to quantify the fire and sediment effects was as follows:

1. Define the historical burn area of the TCAB and PR watersheds over the past 30 years.
2. Incorporate climate change projections of burn area to estimate future 30-year burn area.
3. Identify a series of fires from the FSim PreT dataset that collectively would achieve this projected future burn area over the next 30 years. Select and map these fire perimeters for both PreT and PostT.
4. Quantify the reduction in fire size as a result of treatment.
5. Quantify the reduction sediment erosion volume over a 30-year period as a result of treatment.
6. Quantify the reduction in sediment volume from a select hillslope debris flow as a result of treatment.
7. Develop a sediment delivery ratio to the total sediment volumes described by the models in order to estimate the potential reduction in the amount of sediment delivered to Tiger Creek Afterbay and Pardee Reservoir as a result of fuel treatments.

We then applied the results of this analysis to the ecosystem services we identified (Chapter 2) to quantify the economic benefits of fuel treatments under these conditions. This includes the value of avoiding dredging, which was calculated by estimating the difference in the sediment delivered to each reservoir pre- and posttreatment (Chapter 6).

3.6.1 Scenario selection

The Mokelumne watershed's 30-year historical burn area was quantified using the CAL FIRE database. Since 1983, a total of 6 large (100 ha or larger) fires have collectively burned approximately 10,000 ha of the combined area of the TCAB and PR catchments (approximately 10% of the 96,000 ha). This estimate of a 10% burn area over 30 years is consistent across the five counties surrounding the Mokelumne watershed, where approximately 162,000 of more than1.6 million ha have burned from 1982 to 2012 (CAL FIRE database).

Looking toward the future, we drew upon work by Cal Adapt to assess regional changes in fire risk, as predicted by a range of global climate models (GCM) and future greenhouse gas emission scenarios (See Chapter 9, and Figure 9.2). The result is an average predicted increase in wildfire burn area of 2.5 times by 2050. Combining the historical burn area with the projected changes in wildfire behavior, we developed a 30-year scenario for the Mokelumne watershed by estimating that 20%, or a 2-fold increase, of the watershed would burn between 2013 and 2043. The result is a scenario in which approximately 19,000 ha would burn over the next 30 years.

The FSim fire perimeter dataset discussed earlier was used to identify potential future fires in the TCAB and PR subwatersheds. A series of potential fire combinations could occur over the next 30 years to achieve the 20% burn area estimate. A fundamental assumption of this approach is that the future climate-adjusted burn areas would be a linear extension of the historical fire size distribution, meaning the future 50th percentile fire (for example) would be twice the size as the historical 50th percentile fire. In order to select potential future fires from our existing modeling datasets, we assumed that at least one large (90th percentile) fire, after being adjusted to future conditions, would occur in both watersheds (TCAB and PR) and fire perimeters would not overlap. Thus, the climate-adjusted 90th percentile burn area for each subwatershed would be two times the existing-conditions size. Figure 3.14 maps the selected fire perimeters PreT and PostT and Table 3.8 summarizes and Table 3.9 defines key metrics. The PreT fire perimeter dataset is used to select the fires to represent the 30-year scenario. The FSim modeling data allows the direct comparison of fires from the same ignition point and their associated size and impacts posttreatment, providing an excellent opportunity to quantify the impact of treatments on future burn area and associated sediment.

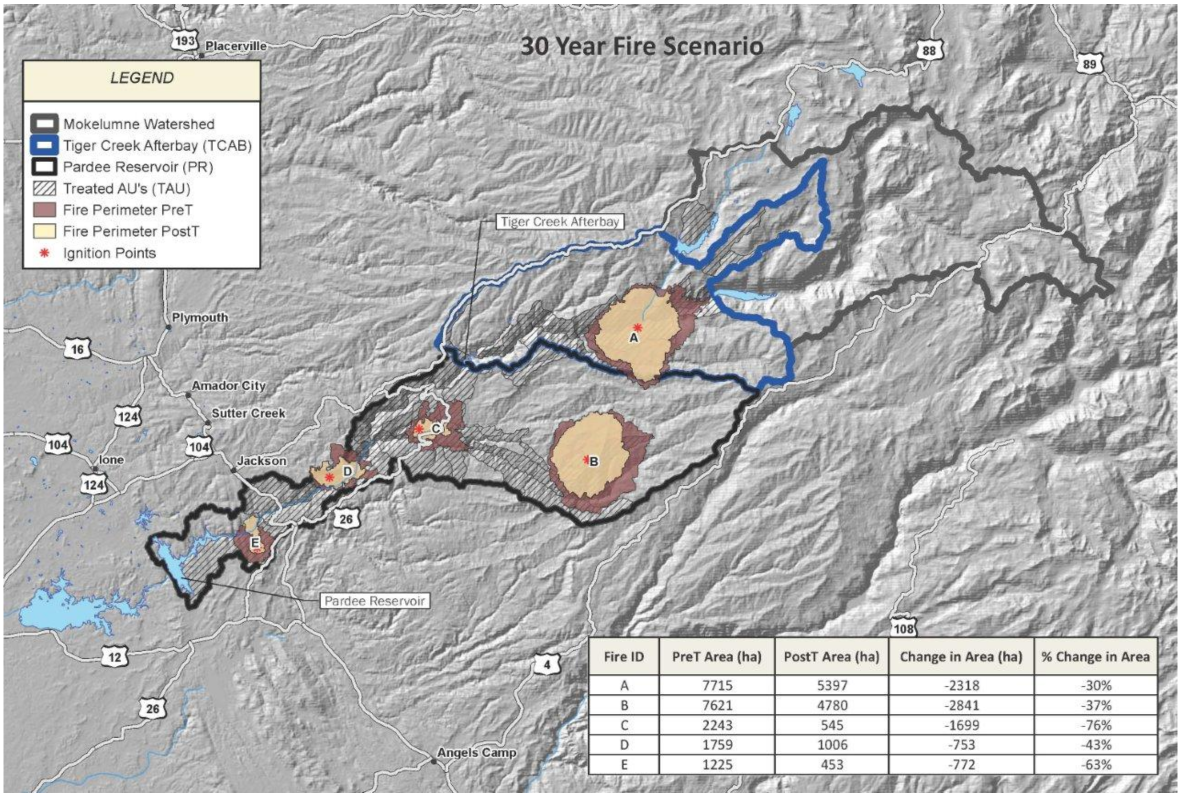
One future TCAB fire was selected and is referred to as Fire A, a 7,715-ha fire that on its own achieves the expected 20% burn area of the TCAB subwatershed. For the PR subwatershed, four fires were selected to represent a range of climate-adjusted potential fire sizes and locations: a 90th percentile fire (B), a 65th percentile fire (C), a 59th percentile fire (D), and a 50th percentile fire (E). Together, these fires achieve the predicted 20% burn area in PR for the next 30 years. Cumulatively, between 2013-2043 in this scenario, PreT fires A-E burn a total of 20,563 ha, or 14% of the total upper Mokelumne watershed. For comparison, the 2013 Rim Fire has burned over 100,000 ha (as of Sept 7, 2013) and is an order of magnitude above the climate-adjusted 90th percentile burn areas used in this analysis, providing support that fire size will dramatically increase within the next 30 years. Given available datasets and the theoretical understanding of the rapidly increasing future risk of wildfires, we believe these scenarios are both reasonable and feasible.

While the likelihood of this actual scenario occurring in the future is extremely small, the FSim modeling allows us to estimate the probability that a fire comparable in size to our scenario would occur over the next 30 years. The 30-year probability of Fires A-E range from 6% to 85% based on historical fire ignitions and historical climatic conditions, as summarized in Table 3.8. Based on the trend of fire seasons growing more and more destructive, there is general consensus that the probability and size of fires will continue to increase (Westerling and Bryant 2008), supporting the idea that the actual 30-year probabilities for these fires are much higher than reported in Table 3.8.

3.6.2 Thirty-year avoided sediment volume as a result of treatment

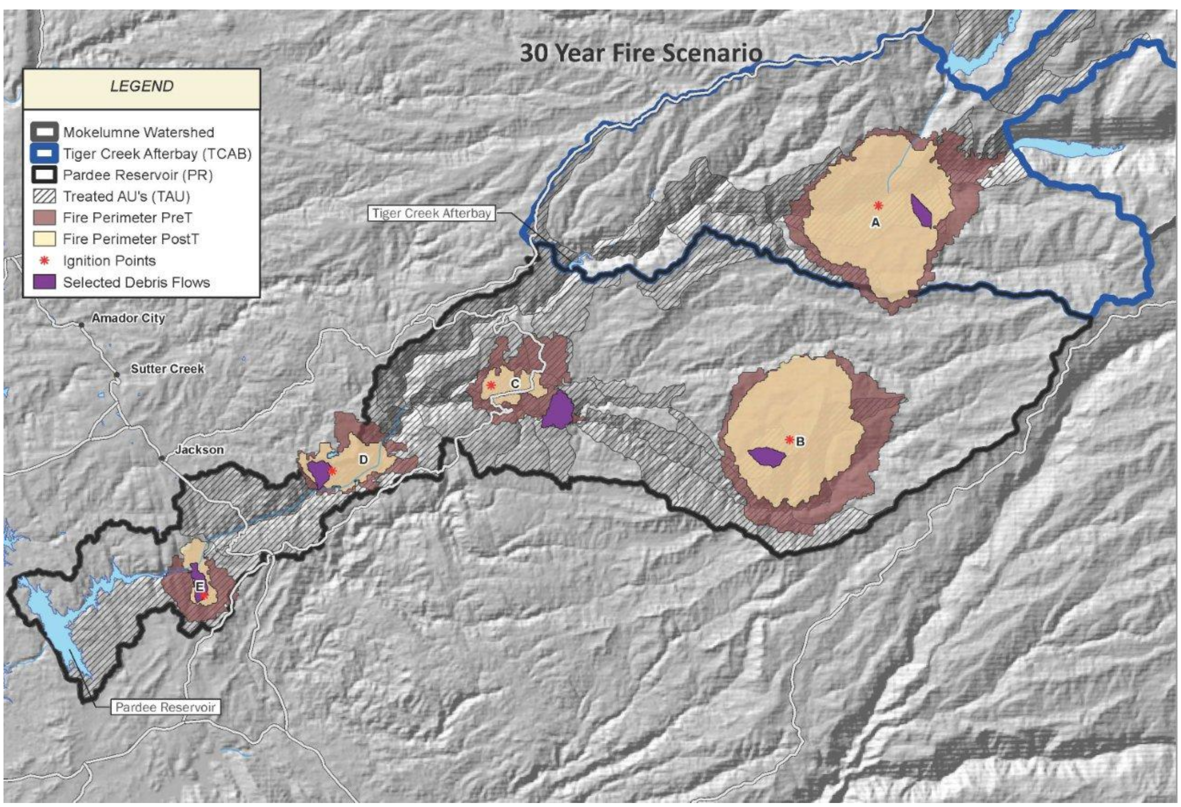
Figure 3.14 illustrates that treatments resulted in a significant reduction in burn area, from 30-76%. The fire perimeters were overlaid with the GeoWEPP model results to determine the relevant sediment volumes generated by surface erosion from these fires. Similarly, the perimeters were overlaid with the debris flow model results to identify the most likely debris flow that would occur as a result of each PreT fire perimeter (Figure 3.15). It is assumed that each of the fires occurs sometime between 2013-2043, but a specific timing within that window is not speculated.

Figure 3.14: 30 year (2013-2043) scenario and the corresponding five fires



Fire ID	PreT Area (ha)	PostT Area (ha)	Change in Area (ha)	% Change in Area
A	7715	5397	-2318	-30%
B	7621	4780	-2841	-37%
C	2243	545	-1699	-76%
D	1759	1006	-753	-43%
E	1225	453	-772	-63%

Figure 3.15: 30 year (2013-2043) scenario, the corresponding five fires, and probable debris flows



For these fires, the postfire surface erosion rates represent only the first postfire year, with erosion rates expected to decrease by 80% in the second year and return to baseline by the third year post fire. The fuel treatments themselves increase erosion rates as a result of soil compaction and disturbance during their implementation, increasing the background erosion rates in the TAU for the first year post treatment. For the 30-year future scenario, erosion rates for untreated and unburned areas were calculated by multiplying the PreT erosion modeling results by 30. To account for fire impacts and achieve the expected 30-year output for the scenario, the two years of increased erosion described by the model were added to 28 years of no-fire PreT sediment volume. The same methodology was applied to describe the impacts of treatments under no-fire conditions, but with one year of increased sediment added to 29 years of PreT erosion rates. The debris flow data were incorporated by assuming that a 25-year 2-hour storm occurred the year following the fires and that the hillside with the highest probability of a debris flow in PreT conditions experienced a debris flow. The associated volume of sediment generated by the debris flow, along with the probability of the flow occurring, can be found in Table 3.8. In one case, the PostT fire perimeter did not burn the selected hillslope, resulting in no PostT debris flow.

Table 3.8 presents the values needed to estimate the cumulative volume of sediment generated and delivered to TCAB and PR for both PreT and PostT conditions. Table 3.9 defines each variable used. The difference in the PreT and PostT sediment generated is termed the *cumulative avoided erosion* and does not include the volume of sediment that results from treatment. The estimates suggest a 92,000 m^3 reduction in sediment erosion in the TCAB watershed and over 400,000 m^3 reduction in the PR watershed. These are significant erosion savings that would equate to the preservation of a myriad of long-term physical and ecological processes critical to supporting the ecosystem services these watersheds provide.

To approximate the volume of sediment delivered to Tiger Creek Afterbay and Pardee Reservoir, we used a sediment delivery ratio (SDR). For every cubic meter of sediment that erodes on the hillsides, a portion of that will make it to the river, and a portion of that will make it downstream and into the reservoir or afterbay. The SDR allows us to estimate how much of the sediment predicted to erode by the models may eventually be delivered to the reservoirs. Two published methods to estimate the SDR were used for TCAB and PR, and the results were averaged to develop reasonable SDRs. Vanoni (1975) used the data from 300 watersheds throughout the world to develop a generalized methodology to predict the percentage of sediment that reaches a reservoir or lake based on the size of the watershed itself ($SDR = 0.42\ A^{-0.125}$). The US Department of Agriculture (1972) described a similar process, but their recommendation differed from that of Vanoni ($SDR = 0.51\ A^{-0.11}$). The predicted SDRs for TCAB and PR are provided in Table 3.8; the result is an estimated volume of avoided sedimentation due to treatments in Tiger Creek Afterbay and Pardee Reservoir by 24,000 and 106,000 m^3, respectively. A discussion of the economic values of avoiding these volumes of sedimentation can be found in Chapter 6.

Table 3.8: Thirty year Five Fires scenario results

30 YR Fire Scenario

Fire area, percentile and probability of occurence using FSim fire perimeter data outputs. See Figure 5.14 for locations.

Watershed	TCAB	PR			
Fire ID	A	B	C	D	E
FIRE Number	11037	12635	14548	5094	14394
PreT Area (ha)	7,715	7,621	2,243	1,759	1,225
PreT Percentile	98	96	80	75	67
PreT % of burned area within treatment area	54%	40%	98%	68%	80%
1YR Prob	0.2%	0.8%	3.8%	4.7%	6.2%
30YR Prob	6%	20%	68%	76%	85%
PostT Area (ha)	5,397	4,780	545	1,006	453
PostT Percentile	96	94	51	67	46
PostT % of burned area within treatment area	56%	43%	100%	71%	58%
Change in Area (ha)	(2,318)	(2,841)	(1,699)	(753)	(772)
Burn area % change	-30%	-37%	-76%	-43%	-63%

Surface Erosion No Fire

Watershed (WS) and fire perimeter (FP) surface erosion (SE) volumes for, with, and without the occurance of fire. SE volumes obtained by intersecting WS and FP boundaries with GeoWepp erosion layers in GIS.

Watershed	TCAB	PR			
WS PreT No Fire SE (m^3/yr)	9,897	7,235			
WS PostT No Fire SE (m^3/yr)	13,103	11,100			
WS PostT No Fire SE % change	32%	53%			
Fire ID	A	B	C	D	E
FP PreT No Fire SE (m^3/yr)	1,521	909	197	667	349
FP PostT No Fire SE (m^3/yr)	1,592	1,095	55	593	116
FP No Fire SE % change	5%	20%	-72%	-11%	-67%

Surface Erosion Post Fire

Fire ID	A	B	C	D	E
FP PreT SE (m^3/yr)	138,343	490,830	20,629	25,484	24,762
FP PostT SE (m^3/yr)	62,724	217,479	1,340	15,295	7,468
FP SE % change	-55%	-56%	-94%	-40%	-70%

Debris Flow Post Fire

Hillslope specific debris flows volumes for both PreT and PostT selected for each fire perimeter as described in the text.

Fire ID	A	B	C	D	E
Highest probability debris flow PreT (annual)	31%	34%	3%	13%	23%
FP PreT DF (m^3/yr)	12,071	19,214	15,639	11,485	8,306
FP PostT DF (m^3/yr)	7,514	12,664	-	11,431	8,150
PostT DF probability (annual)	1%	1%	0%	12%	18%
DF volume % change	-38%	-34%	-100%	0%	-2%
DF probability reduction	30%	33%	3%	1%	4%

PreT Conditions

Estimate of total sediment eroded from each watershed in existing conditions.

Watershed	TCAB	PR
Year 1 post fire (m^3)	158,790	621,462
Year 2 post fire (m^3)	36,045	117,454
28 years no fire (m^3)	277,107	202,583
30 YR Sediment Generation (m^3)	471,941	941,498

PostT Conditions

Estimate of total sediment eroded from each watershed following implementation of fuels treatment program.

Watershed	TCAB	PR
Year 1 post fire (m^3)	78,614	278,940
Year 2 post fire (m^3)	20,849	48,608
28 years no fire (m^3)	280,313	206,448
30 YR Sediment Generation (m^3)	379,776	533,996

Treatment Effects

Total erosion and sedimentation to resevoirs avoided as a result of fuels treatment.

Watershed	TCAB	PR
Cumulative avoided erosion (m^3)	92,166	407,502
Sediment delivery ratio (SDR)	0.26	0.25
Avoided sediment load to reservoir (m^3)	23,963	105,951

Table 3.9: Thirty year Five Fires scenario terms – Definition of terms used in Table 3.8

Fire Perimeter Facts	
Fire ID	Figure 5.14 ID
Thread Year	FSim thread year modelled
FIRE Number	FSim fire number modelled
PreT Area (ha)	Burn area in existing conditions
PreT Percentile	Percentile of burn area within PreT fire perimeter dataset (Figures 5.12, 5.13)
1YR Prob	Probability of occurance in any one year given PreT fire perimeter data.
30YR Prob	Probability of fire of this size occuring once in 30 yrs given PreT fire perimeter data, where 30YR Prob = 1-(1-1YRProb)^30
PostT Area (ha)	Burn area in treated conditions
PostT Percentile	Percentile of burn area within PreT fire perimeter dataset (Figures 5.12, 5.13)
Change in Area (ha)	PostT-PreT area
Burn area % change	(PostT-PreT area)/PreT area
Watershed Surface Erosion Volumes No Fire	
WS PreT No Fire SE (m^3/yr)	Watershed in existing conditions surface erosion volume given no fire occurs. Thresholds represent existing conditions and serve as the baseline for many comparisons of the effects of fuel treatments.
WS PostT No Fire SE (m^3/yr)	Watershed in treated conditions surface erosion volume given no fire occurs. Assume this is representative erosion rate 1yr post treatment.
WS PostT No Fire SE % change	Calculated % change.
Fire Perimeter Surface Erosion Volumes No Fire	
FP PreT No Fire SE (m^3/yr)	No fire surface erosion volume for the respective fire burn area in existing conditions.
FP PostT No Fire SE (m^3/yr)	No fire surface erosion volume for the respective fire burn area in treated conditions.
FP No Fire SE % change	Calculated % change.
Fire Perimeter Surface Erosion Volumes One Year Post Fire	
FP PreT SE (m^3/yr)	Surface erosion volume for the respective fire burn area in existing conditions for the one year post fire.
FP PostT SE (m^3/yr)	Surface erosion volume for the respective fire burn area in treated conditions for the one year post fire.
FP SE % change	Calculated % change.
Hillslope Debris Flow Volumes and Probability One Year Post Fire	
Probability of DF PreT (annual)	The probability of the selected hillslope to experience a debris flow within the PreT fire perimeter boundary. Highest probability hillslope DF within the PreT fire perimeter boundary was selected.
FP PreT DF (m^3/yr)	Debris flow volume for the selected hillslope in existing conditions.
FP PostT DF (m^3/yr)	Debris flow volume for the selected hillslope in treated conditions. If the hillslope was not burned by the PostT fire, the FP PostT DF = 0.
PostT DF probability (annual)	The PostT probability of the selected hillslope DF.
DF volume % change	Calculated % change.
DF probability reduction	Calculated reduction.
PreT and PostT 30yr Sediment Generation	
Year 1 post fire (m^3)	Total volume of sediment eroded from the catchment the year post fire.
Year 2 post fire (m^3)	Total volume of sediment eroded from the catchment the second year post fire.
28 years no fire (m^3)	Total volume of sediment eroded from the catchment all 28 yrs unburned.
30 YR Sediment Generation (m^3)	Sum of above
Treatment Effects	
Cumulative avoided erosion (m^3)	Total 30yr sediment generated PreT - PostT
Sediment delivery ratio (SDR)	Fraction of the sediment generated that is predicted to reach the respective reservoirs
Avoided sediment load to reservoir (m^3)	Cumulative avoided erosion * SDR

3.7 Conclusions

As expected, the effects of fuel treatments on fire and erosion behavior are greatest within close proximity of the TAUs. The potential severity and extent of postfire erosion are extremely sensitive to the winter storm conditions in the year after the fire. The surface erosion estimates are based on an average postfire winter season, while the debris flow model is based on the occurrence of an extreme 25-year storm event.[4] Should an above-average winter snowfall or spring rain-on-snow event occur following a fire, the erosional damage within the burned area could be significantly worse than our modeling results portray. The ability of the forest and riparian ecosystems to recover from such erosional modifications could take decades and the no-treatment scenarios we have modeled have the ability to permanently alter the topography and hydrology of the local system.

The model results support the hypothesis that fuel management will substantially reduce the likelihood and size of fires in the upper Mokelumne watershed and these reductions in burn area will substantially reduce the risk and scale of postfire surface erosion, debris flows, and other mass-wasting events, as well as to natural and human resources. Given the future climatic projections of hotter, drier summers superimposed on severe fuel accumulation from decades of fire suppression and limited implementation of fuel treatments, actions such as those modeled here could mitigate problems on a scale we have not yet experienced. Based on the events of the last decade, it is thought that many California forests are at a tipping point, where future fires will occur more frequently and burn greater areas at higher intensities than is suggested by the historical record. The implementation of and long-term commitment to an effective fuel management program could serve as a valuable adaptation strategy to reduce the potential impacts of future climate change on the local forest and riparian ecosystems, as discussed in Chapter 9.

3.8 Assumptions and Limitations

A number of assumptions and limitations are noted throughout the document, but the critical assumptions and limitations of this effort are summarized here:

- All of the documented effects of fuel treatments are based on the fundamental assumptions that 1) all of the treated-landscape conditions exist at the same point in time, 2) treated landscapes are maintained as modeled, and 3) all untreated locations remain in 2008 conditions. While these are unrealistic assumptions when considering the reality of the forest system and management over time, this modeling exercise provides insight into current fire and sediment behavior, in addition to defensible estimates of the benefits from a fuel treatments program. The consistency in all other model parameters for PreT and PostT scenarios appropriately isolates changes due solely to reductions in fuels.

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[4] FERGI model results are based on a 2.5-year storm and gully dimensions from gullies formed during a 10-year storm.

- FSim simulations are based on the recent historical climate (20 years). While projections of future climatic conditions vary dramatically, there is general consensus that past climate is not representative of the future (see Chapter 9). Therefore, future fire occurrence could be much greater than that simulated by FSim. Reasonable adjustments and assumptions were used to incorporate climate change impacts into the 30 year hypothetical scenarios for both TCAB and PR. The maximum fire size modeled by this effort was 33,000 ha; applying the climate adjustments outlined in this chapter we would predict a maximum future fire of 66,000 ha by 2040. However, the 2013 Rim Fire has consumed more than 130,000 ha in similar terrain and stand conditions, suggesting future burn areas may increase by considerably more than discussed here.

- FSim simulations are based on and calibrated to the recent historical fire occurrence (20 years) in the region surrounding the upper Mokelumne watershed. However, due to the extraordinary variability in the occurrence of large fires, historical fire occurrence (the mean annual number of wildfires and associated land area burned) is not necessarily a reliable predictor of current or future fire occurrence. This is clearly demonstrated by the 2013 fire season. Prior to the 2013, fire season, the two largest wildfires in the five counties around the upper Mokelumne watershed were the 1996 Ackerson Fire in Yosemite National Park, burning 23,921 ha, and the 1987 Paper Fire in Stanislaus, NF, with a total burn area of 21,426 ha. The largest fire simulated in FSim was 33,000 ha. In contrast, the 2013 Rim Fire has burned more than 130,000 ha. In fact, in recorded fire history, the Rim Fire is the Sierra Nevada's largest fire, a devastating 40% larger than the next largest fire, the McNally Fire of 2002.

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Chapter 4: Fire Suppression Costs

4.1 Introduction

In this section, we discuss wildfire suppression implications of fuel treatment in the Mokelumne watershed. First, we describe the general effects of fuel treatment on wildfire suppression costs, risks, and success. Then, we provide estimates of suppression costs for the five fires with and without prior fuel treatment. We use existing reviews of fire suppression costs, with an emphasis on fires that occurred in California. Based on our research and modeling, we estimate that the savings from avoided future suppression and rehabilitation costs would pay for between 50% and 70% of the treatment costs. Table 4.1 summarizes the cost and avoided cost findings in this chapter.

Table 4.1: Costs and avoided costs from modeled fuel treatment

	No treatments		Treatments		Avoided costs	
	Low estimate	High estimate	Low estimate	High estimate	Low estimate	High estimate
Fire suppression and rehabilitation costs (millions)	$ 55.0	$ 73.0	$ 20.0	$ 29.7	$ 35.0	$ 43.3

4.2 Per Acre Suppression Costs

Wildfire suppression costs are an increasing burden for taxpayers. This has motivated research into the factors driving costs, including direction by Congress for federal agencies to investigate suppression costs. Increasing fuel loads, drought conditions, temperatures, forest disease and infestation, and development in the wildland-urban interface (WUI) all contribute to increasing wildfire occurrence, wildfire size, and costs of suppression efforts (Donovan, Noordijk, and Radeloff 2004; Stephens and Ruth 2005). In addition, varied elevation and topography can increase suppression costs through difficulty of access, while fire intensity and rate of spread can limit ground personnel use, both of which can require the use of expensive resources such as aircraft (Gebert et al. 2007; Gude et al. 2012; Prestemon et al. 2008; Preisler et al. 2011).

With the increasing share of the federal land management agencies' budgets required for suppression, Congress has requested cost reviews for large wildfires with federal suppression costs of more than $10 million. Based on the two most recent reviews, for the 2008 and 2009 fire seasons, a majority of the most costly U.S. fires occurred in California: 17 of 22 in 2008, and five of six in 2009 (Large-Cost Fire Independent Review Panel, 2010). California's most costly wildfires in 2008 ranged in size from 6,112 to 192,038 acres and had overall average suppression costs of $645 per acre. Individually, the suppression costs for the 17 largest 2008 wildfires reviewed in

California ranged in cost from $168 to $2,055 per acre. The 2009 wildfires reviewed in California had per acre suppression costs of $390 to $2,672. These fires don't show a strong correlation between size of wildfire and cost per acre, suggesting that other details—such as terrain and proximity to the WUI—were more of a factor in cost than size alone.

Western Forestry Leadership Coalition (WFLC) conducted six case studies in the Western United States looking at several categories of wildfire costs. These case studies were based on fires that occurred between 2000–2003 in Montana, New Mexico, Colorado (2), Arizona, and California. For these six wildfires, suppression costs ranged from $9.5 to $61 million per fire, or $101 to $781 per acre (WFLC 2010). The case studies also considered the rehabilitation costs for cleanup and recovery following these fires. The rehabilitation costs per acre for the six fires ranged widely, with per acre averages of $123, $184, $290, $300, $1,688 and $4,277. Thompson et al. (2013) compiled the average costs to the United States Forest Service (USFS) for fires larger than 300 acres and found an average per acre cost of $2,117. Gebert et al. (2007) examined suppression expenditures for 1,550 large wildland fires from 1995–2004 and identified an average cost of $2,114 per acre for fires in California, the highest of any region (USFS Region 5).

4.3 Fuel Treatments and Suppression Effort

Previous research has shown that fuel treatments alter not only wildland fire size, but also burn probabilities, fire severity, and fire behavior (Ager et al. 2010; Ager et al. 2011; Calkin et al. 2005; Cochrane et al. 2012). Fuel treatments can further reduce suppression costs by enhancing the effectiveness of fire suppression efforts via increased visibility, safer access and crew mobility, and reduced heat and smoke (Bostwick et al. 2011; Moghaddas and Craggs 2007; Murphy et al. 2007). Suppression activities often involve mechanical and prescribed burn treatments that are similar to typical fuel treatments, but are often more extreme than an ecologically derived fuel treatment. Fire crews find it easier to defend structures where fuels have been treated because they are able to more safely establish defensible positions. For this reason, it is now state law that homes in the WUI have at least 100 feet of what is known as defensible space. Treatments that extend beyond, or work in tandem with, Defensible Space zones, further contribute to the safety of fire crews and their ability to more effectively manage the fire.

The 2007 Antelope Complex Fire in Plumas National Forest (northern California) affected areas that had received prior fuel treatments. A review of the effects of fuel treatments on suppression effort yielded the following key findings:

- *Treated areas had significantly reduced fire behavior and tree and soil impacts compared to untreated areas.*
- *Treated areas along several flanks of the fire were used during suppression for both direct attack with dozers and handcrews, as well as for indirect attack with burn operations.*
- *Treated areas that burned during the first two days—when suppression resources were limited and fire behavior more uniformly intense—had reduced fire effects compared to untreated areas. In some areas, these treated sites had moderate to high severity effects.*
- *A defensible fuel profile zone provided a safe escape route for firefighters when the column collapsed and two other escape routes were cut off by the fire (Fites et al. 2007).*

Also in 2007, the Angora Fire in the Lake Tahoe area burned about 3,000 acres and suppression costs exceeded $11 million, or approximately $3,500 an acre. Of the acreage that burned, just under half had been previously treated by the USFS, state agencies, or private landowners (USDA Forest Service 2007). Overall, when the high-intensity crown fires reached treated areas, the fire dropped down to a surface fire within 150 feet of the treatment area boundary, which enhanced suppression effectiveness (Safford, Schmidt, and Carlson 2009). The treatment areas that did burn with high intensity were largely the result of being located on steep slopes that were downwind from untreated areas. Two reasons these areas burned at a higher intensity were that fuel treatments were lighter on the steepest slopes to prevent soil erosion, and in these areas the momentum of the crown fires from the untreated areas was able to overcome the spacing and reduced fuel loads of the treated areas (Murphy, Duncan, and Dillingham 2010). Of the treated acreage on USFS land that burned, 405 acres burned as a ground fire and 75 acres burned as a crown fire, compared with the untreated areas where most of the acreage burned as crown fire and experienced 95% or greater mortality (Safford, Schmidt, and Carlson 2009).

In a comprehensive review of the effect of fuel treatments on wildfire behavior and suppression costs in northern California, the USFS reviewed 20 wildfires from 1999 to 2010 that interacted with fuel treatments (Murphy, Duncan, and Dillingham 2010). The key findings of this study included:

- *Untreated areas experienced the most severe fire effects and vegetative mortality.*
- *Treated areas increased fire suppression options and enhanced opportunities for safe, low-severity burnout operations with reduced potential for spotting and torching.*
- *Smoke volume was reduced significantly when fire reached treated areas.*

This review also provided accounts from ground crews fighting the fires when the fires encountered treated areas, including:

> *"The fire entering fuel treatments resulted in an abrupt change in fire behavior. Some treatment units stopped the advancing wildfire with little to no suppression effort."*

> *"Fuel treatments allowed suppression crews to conduct burnout operations safely and effectively. Spot fires were easily detected and contained. Treated areas reduced fire behavior, providing for safe egress of fire crews during extreme fire behavior."*

> *"Fuel treatments allowed limited suppression resources to be effective. Treated areas provided anchor points, increased production rates, and allowed effective application of aerial retardant."*

> *"Open stands lowered fire intensity, allowing suppression crews safe access and direct attack. This resulted in smaller final fire size and reduced suppression costs."*

These studies and other accounts suggest that fuel treatment can influence suppression costs, suppression effort success, and wildfire risk to fire crews in numerous beneficial ways.

Fitch et al. (2013) modeled the effects of forest restoration treatments in Arizona's Four Forest Restoration Initiative on fire behavior characteristics and fire suppression costs. Controlling for fire size, they found that alteration of fire behavior and severity alone can decrease fire suppression costs. Total wildfire suppression costs tended to increase as both the distance from the wildfire to the WUI became smaller and as a greater proportion of fires burned at high-burn severity. They estimate a range for wildland suppression costs for similar-sized fires and conditions at $706 to $825 per acre for untreated landscapes, compared with $287 to $327 per acre in treated areas, an approximately 60% reduction.

4.4 Rim Fire Lessons

The 2013 Rim Fire burned 257,314 acres and cost $127.4 million, approximately $495 per acre (InciWeb 2013). Final suppression costs for the Rim Fire are not available at the time of this writing. The Rim Fire occurred in the watershed just south of the Mokelumne, so it provides useful insights regarding suppression activities in an area that is similar to the Mokelumne watershed and has similar land management. A USFS preliminary review of the effect of fuel treatment on suppression efforts identified a fuel break and adjacent fuel treatments that allowed successful defense of the communities of Pine Mountain Lake, Groveland, and Big Oak Flat. Fire crews reported that they would likely have been unable to defend a series of homes and leased cabins amongst a 742-acre treatment project if not for the treatment. With the treatments to support their efforts, the fire crews were successful in defending these structures. Crews also reported that other treatments sufficiently slowed the progress of the fire to allow them to defend structures within Yosemite National Park (Johnson et al. 2013).

4.5 Fire Scenario Suppression Cost Estimates

The wide array of wildfire suppression costs observed in California makes it difficult to choose a narrow estimate for likely suppression costs. Fires similar to the scenarios in this report have ranged in per acre cost from hundreds to thousands of dollars. The total burned area of a wildfire is not the only determinant of cost, and in the Mokelumne watershed, vegetation, topography, accessibility, and proximity to valuable structures have the potential to contribute to high suppression costs. Evidence from similar fires described above suggests that fuel treatments can decrease suppression costs. The fire model runs provide flame length data that are influenced by the location of fuel treatments. For our suppression cost estimates, we use per acre suppression costs at the higher end of the observed range for areas of high flame lengths (>8 ft.) and the lower end for low flame lengths (<8 ft.). Given the recorded costs of wildfires in California and the Fitch (2013) study for suppression costs in treated versus untreated areas, we use $200 to $500 for the per acre cost in low flame-length areas, and $1,000 to $1,500 for high flame-length areas. We do not adjust for inflation because recent fire suppression costs still fall within these ranges.

Across the five simulated fires (A-E), the overall decline in burned area with fuel treatments is 41%. More dramatically, the area of high flame length within the fires declined by 75 percent. We apply the assumptions on suppression costs described above to each fire, based on area of high flame length and low flame length (Table 4.2). The low estimate for each range in Table 4.2 is based on the low-end suppression cost estimates, and the high estimate is based on the high-end suppression cost estimates. As demonstrated above, large wildfires in California have generated suppression costs higher than the high-end estimates we use, so our high-cost estimates might underestimate the true cost for some areas within the watershed. In general, these estimates suggest suppression costs without treatment ranging from $21 to $39 million, and avoided suppression costs from treatment of $13 to $21 million.

Table 4.2: Suppression cost estimates, with and without fuel treatments ($ million)

	Pre-treatment suppression costs		Post-treatment suppression costs		Avoided costs	
Fire ID	Low estimate	High estimate	Low estimate	High estimate	Low estimate	High estimate
A	$7.1	$13.6	$3.3	$7.5	$3.8	$6.1
B	$9.7	$16.8	$4.2	$8.2	$5.5	$8.7
C	$1.8	$3.7	$0.3	$0.7	$1.6	$3.0
D	$1.5	$3.0	$0.7	$1.5	$0.8	$1.5
E	$1.2	$2.3	$0.4	$0.8	$0.9	$1.6
Total	*$21.4*	*$39.4*	*$8.9*	*$18.6*	*$12.5*	*$20.8*

Source: ECONorthwest. See text for description of assumptions and calculations.

4.6 Rehabilitation Cost Estimates

The suppression cost estimates above do not include post-fire rehabilitation costs. Based on the rehabilitation cost estimates from the WFLC case studies, we assume rehabilitation costs for areas of low flame length and high flame length would respectively correspond to the low and high estimates. The WFLC per acre rehabilitation costs for the case studies ranged from $123 to $4,277 per acre for each fire.[1] If we assume $150 per acre for rehabilitation costs in areas of low flame length, and $2,000 per acre for areas of high flame length, pretreatment rehabilitation costs would be $33.6 million and post-treatment costs would be $11.1 million, for avoided rehabilitation costs of $22.5 million.[2]

4.7 Summary

Summing the low estimates for suppression and rehabilitation in the no-treatment option for this modeled scenario results in $55 million in costs ($21.4 + $33.6). At the high end it could reach $73 million in costs ($39.4 + $33.6). Performing the fuel treatments, which themselves cost $68 million, would save between $23.6 ($12.5 + $11.1) and $31.9 ($20.8 + $11.1) million dollars.

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[1] These are in the original dollars from 2000 to 2003, unadjusted for inflation. Review with experts suggests no substantial changes in these cost ranges to-date.

[2] $150 is at the low end of the range of rehabilitation costs from the WFLC study, and $2,000 is the mid-range value from the study. This range is already quite broad, but given the observed range, an upper estimate could justifiably be higher.

Therefore, after factoring in the expected suppression and rehabilitation cost savings provided by the treatments, the cost of treating all of this land would be between $36 million and $45 million for the modeled scenario.

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Chapter 5: Postfire Infrastructure Damages and Values

5.1 Introduction

The footprints of the Five Fire scenario described in Chapter 3 overlap with homes, businesses, public infrastructure, private utility infrastructure, and timber-producing lands. In this section, we measure the value of land, structures, and timber that fall within the fire footprints, as well as estimate the value that is saved due to the smaller footprints associated with the modeled fuel treatment. Depending on the infrastructure type, we consider the value of either damages from total loss or the repair of less-damaged infrastructure. For lands within the fire footprint in the treated scenario, we calculate the value of potential damages avoided as a result of lower fire intensity. This is calculated from the differences in flame length between treated and untreated scenarios (see Chapter 3 for more on the differences in flame length and fire severity). In later chapters we discuss and value the indirect effects of these wildfire scenarios (see chapters 6 - 8).

5.2 Summary of Findings

Table 5.1 summarizes the results presented in this chapter. It is important to note that the summary only considers changes in impacts based on the difference in the sizes of the fire footprints that are the result of fuel treatments. Please see Table 5.4 for how the change in fire severity due to the modeled fuel treatments within the fire footprints is expected to affect parcel values.

Table 5.1: Summary of findings based on the change in fire footprint size due to fuel treatments

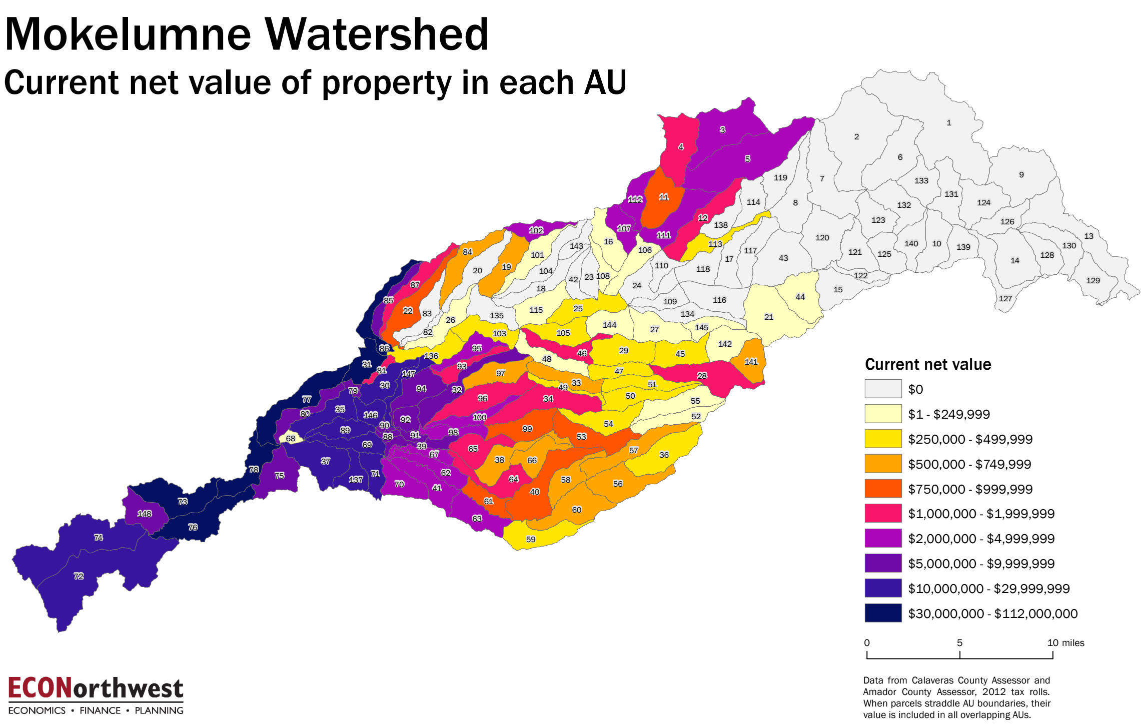
	Hectares burned	*Land value damage (millions)*	*Structural improve-ment value (millions)*	*Canals impacted (miles)*	*Roads impacted (miles)*	*Roads - costs of repairs (millions)*	*Trans-mission lines impacted (miles)*	*Trans-mission line - costs of repairs (millions)*
Without treatment	18,359	$39.2	$63.2	14.4	235	$16.0	1.81	$3.1
With treatment	11,078	$14.6	$17.6	9.9	147	$7.4	0.85	$1.5
Difference	7281	$24.6	$45.6	4.5	88	$8.6	0.96	$1.6

5.3 Value of Land and Structures (Non-Utility)

Communities in the Mokelumne watershed are concentrated in the lower portions of the watershed. Residences and commercial activity account for the majority of the net (land and structure) value in the lower watershed, while land is the primary component of value in the upper watershed (Figure 5.1). We used Amador County and Calaveras County assessor data on assessed property values for analyses in this section. The assessor data may underestimate property value because of a fixed maximum 2% annual increase in assessed property values in California, due to

Proposition 13 (1978) tying values to most-recent sales.[1] For some parcels, however, these estimates might be overestimates if fire does not result in total structural loss. County assessor data do not include value estimates for undeveloped public lands, which is why many areas in Figure 5.1 and Figure 5.2 are not valued within the data we used.

Figure 5.1: Net value of property in the Mokelumne watershed (land and structures)

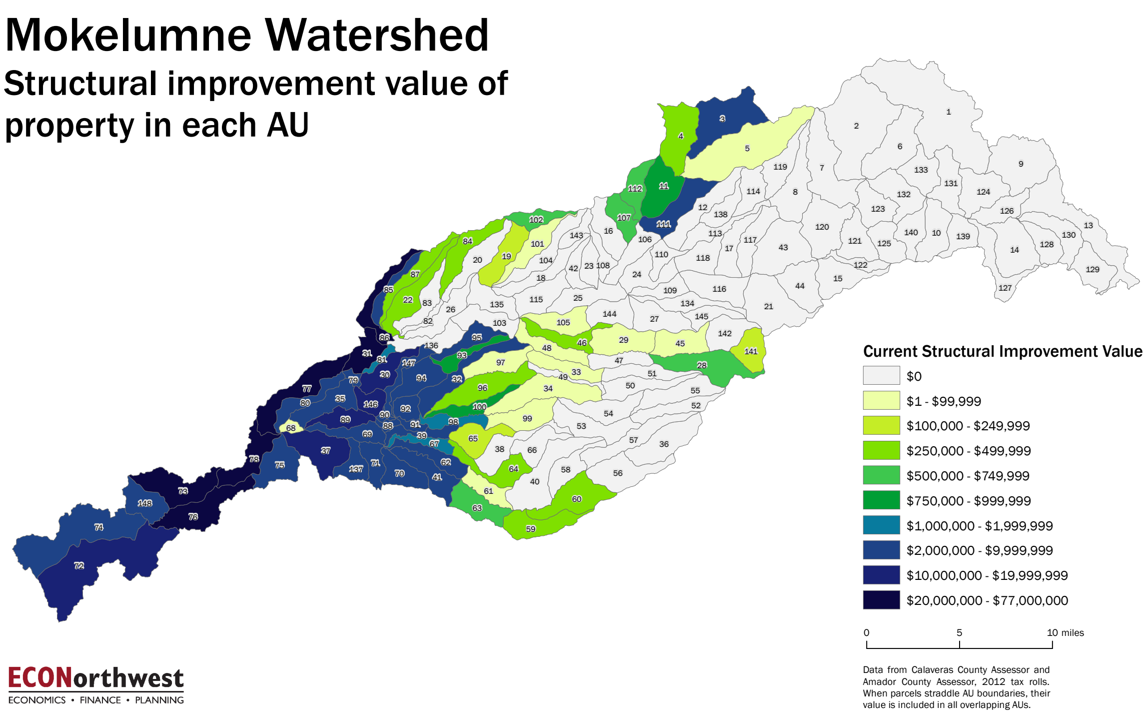


When a parcel falls within the modeled fire perimeters, we use the value for the entire parcel because we cannot identify where in the parcels the valuable structures and assets are located. Because the fire perimeters are unbroken, these edge effects are rare and most of the affected parcels had fire across the full area. The total land area of the affected parcels equals 90% of the area of the fires. Thus we use the portion of intersected parcels that extend beyond the fire footprint as a proxy for an equivalent portion of the area not covered by assessor data. For the remaining 10% of the fire footprints not covered by assessor data, we use half the value of average per hectare values for timberlands, and include those values separately. The remaining land not covered by the parcel data is public, primarily Bureau of Land Management (BLM) and US Forest Service (USFS) land. In this section, we consider only the differences between lands that fall within an untreated scenario fire perimeter, not those within the treated scenario modeled fire

[1]Rapid increases in property value are more typically a result of market demand rather than increases in structural supply costs (materials and labor). Consequently, rapidly increasing property values that outpace assessed value do not likely correspond to rapidly increasing replacement cost as well, in terms of repair or reconstruction.

perimeter. Later in this chapter, we look at the impact that reduced fire severity from treatments may have on structural values.

Figure 5.2: Structural improvement value of property in the Mokelumne watershed



The land value of all parcels in the Mokelumne watershed in Amador and Calaveras counties, for which assessor data are available, is $241 million (Alpine County, located at the highest elevations within the Mokelumne watershed, falls outside of our modeled fire perimeters). The corresponding structural value is $409 million, for a total of $650 million. Table 5.2 shows the aggregated values available from assessor data for parcels that lie within the perimeters of the five fires. The 18,359 hectares of parcels with assessor data in the untreated baseline scenario have a total assessed value of $99 million, while the 11,078 hectares in the treated scenario have a net value of $32 million. It is unlikely that the full $68 million difference in value would be lost, because much of this land would still hold some, if diminished, value. However, there is no standardized methodology for predicting the change in value based on fire modeling, and therefore we include the full value change in this report to highlight the potential change in value that is possible.

Structures, on the other hand, are more likely to lose their full value, and the difference in structural value between the two scenarios is $46 million. While all structures might not be totally lost, repair and removal costs (which are not included in our analysis), could be substantial. The magnitude of the values at risk corresponds to the amount of human development in the area. Areas in the higher elevation reaches of the watershed have fewer structures, while areas lower in

Table 5.2: Impacts on parcels, by fire perimeters (millions $)

	Pretreatment	*Posttreatment*	*Difference*	*Percent decrease in value loss*
Hectares	18,359	11,078	7,282	40%
Land value	$39.2	$14.6	$24.7	63%
Structural improvement value	$63.2	$17.6	$45.6	72%
Net value	$99.4	$31.7	$67.7	68%

Source: ECONorthwest, with data from Amador and Calaveras county assessors.

the watershed contain significant wildland-urban interface (WUI) areas, and therefore have more value at risk. Based on our modeling, the fuel treatments reduced the footprint of the fires and therefore reduced the number of parcels exposed to the modeled fires.

The assessor data also provide a description of the land use for each parcel. We provide a breakdown of values at risk by land use type in Table 5.3. The majority of hectares within the fire perimeters are used for timber production, and are primarily owned by Sierra Pacific Industries. While the value of timberland is not primarily in built structures, the timber value itself is at risk by wildfire, which is accounted for within the value of the land. The majority of structural values are associated with residential parcels.

In addition to decreasing the extent of fire, fuel treatments can also alter the severity of the fire within the perimeter. We assume flame lengths from 0-4 feet as low severity, 4-8 feet as moderate severity, and over 8 feet as high severity. In high-severity fire areas, and their associated longer flame lengths, complete destruction is more likely than in areas with shorter flame lengths. This is because lower flame lengths allow fire fighters to more safely protect structures and land. Therefore, in low severity areas we would expect partial losses to no damage at all of property and structures. Table 5.4 and Figure 5.4 show that, with fuel treatments, the total assessed value of property and structures exposed to low-intensity fire increases, while the total value of property and structures exposed to moderate- and high-intensity fire decreases. The important trend to take from Table 5.4 is that the area of high and moderate severity generally decrease with treatment. This is because the treatments affected fire behavior and many of the lands that burned at high severity under untreated conditions burn at lower intensities under treated conditions.

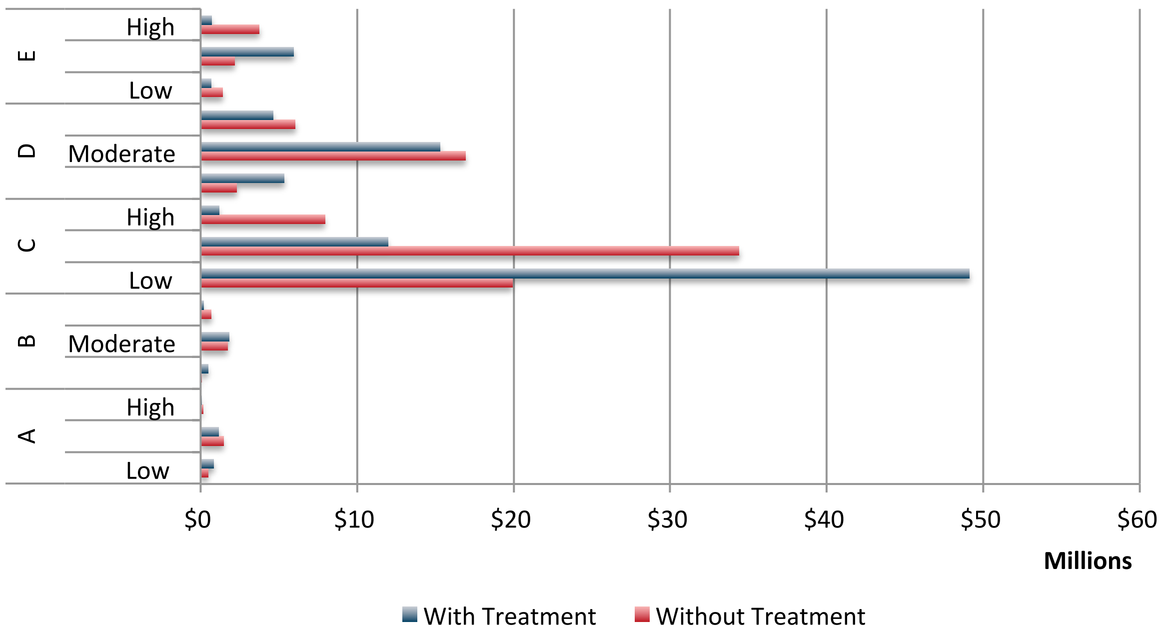
These data suggest that treated parcels and timberlands within fire perimeters are at substantially less risk to damage than if they had been untreated. Firefighters often report that treated lands provide more suitable conditions for successfully defending structures, as well as safer conditions for fire crews to access fire and more effectively suppress it.

Table 5.3: Impacts on parcels, by fire perimeters and land use

Land use	Category	Without treatment	With treatment	Decrease	Percent decrease in lost value
Agriculture	Hectares	2,043	1,405	638	31%
	Land value	$2.1	$1.4	$0.7	34%
	Structural improvement value	$2.7	$0.8	$1.9	69%
	Net value	$4.9	$2.2	$2.7	54%
Commercial	Hectares	8	3	6	67%
	Land value	$0.9	$0.0	$0.9	98%
	Structural improvement value	$2.3	$0.4	$1.9	82%
	Net value	$3.0	$0.4	$2.6	86%
Ranches/ Ranchettes	Hectares	2,220	837	1,383	62%
	Land value	$11.4	$4.3	$7.1	62%
	Structural improvement value	$15.3	$4.5	$10.8	70%
	Net value	$26.3	$8.8	$17.5	67%
Residential	Hectares	1,294	504	790	61%
	Land value	$19.9	$5.9	$14.1	71%
	Structural improvement value	$41.2	$11.3	$29.9	73%
	Net value	$59.0	$16.7	$42.3	72%
Timber production	Hectares	12,312	8,111	4,201	34%
	Land value	$3.6	$2.4	$1.2	33%
	Structural improvement value	$0.2	$0.0	$0.2	93%
	Net value	$3.8	$2.4	$1.4	37%
Other	Hectares	482	218	264	55%
	Land value	$1.3	$0.6	$0.7	54%
	Structural improvement value	$1.5	$0.5	$1.0	65%
	Net value	$2.4	$1.1	$1.3	54%

Source: ECONorthwest, with data from Amador and Calaveras county assessors.

Figure 5.3: Modeled fire impacts on parcels, by fire severity, for the five modeled scenarios



Note: Low = 0-4 ft. flames, Moderate = 4-8 ft. flames, and High = 8 ft. + flames. Source: ECONorthwest, with data from Amador and Calaveras county assessors.

Table 5.4: Modeled impacts of fire severity on parcels, based on the five fire scenario

Fire	*Fire severity category*	*Without treatment*	*With treatment*	*Change*	*% change in value of parcels affected*
A	Low	$0.5	$0.8	$0.4	77%
	Moderate	$1.5	$1.2	-$0.3	-21%
	High	$0.15	$0.08	-$0.065	-44%
B	Low	$0.1	$0.5	$0.4	633%
	Moderate	$1.7	$1.8	$0.1	6%
	High	$0.7	$0.2	-$0.5	-74%
C	Low	$19.9	$49.1	$29.2	147%
	Moderate	$34.4	$12.0	-$22.4	-65%
	High	$7.9	$1.2	-$6.7	-85%
D	Low	$2.3	$5.3	$3.0	132%
	Moderate	$16.9	$15.3	-$1.6	-10%
	High	$6.0	$4.6	-$1.4	-23%
E	Low	$1.4	$0.7	-$0.7-	-52%
	Moderate	$2.2	$5.9	$3.8	174%
	High	$3.8	$0.7	-$3.0	-81%

Note: Low = 0-4 ft. flames, Moderate = 4-8 ft. flames, and High = 8 ft. + flames. Source: ECONorthwest, with data from Amador and Calaveras county assessors.

5.4 Canals and Powerhouses

The 17-mile concrete canal from Salt Springs to Tiger Creek is the only above-ground conveyance in the Mokelumne watershed analysis area; fuel treatments reduce the miles of canal exposed to fire by 31%. Of the 14 miles within the untreated fire footprint (Table 5.5 and Figure 5.3) over 10 of these miles are within Fire A and the remaining miles are within Fires C and D. While wildfires may not directly affect the canal, they can increase the severity of floods and mudslides. A landslide through the canal can destroy an entire section of canal, but less dramatic events, such as a small slide that fills the canal with debris, can also be costly. The cost of damage to canals and water conveyance structures depend heavily on the circumstances, and information is not readily available to reasonably estimate potential costs.

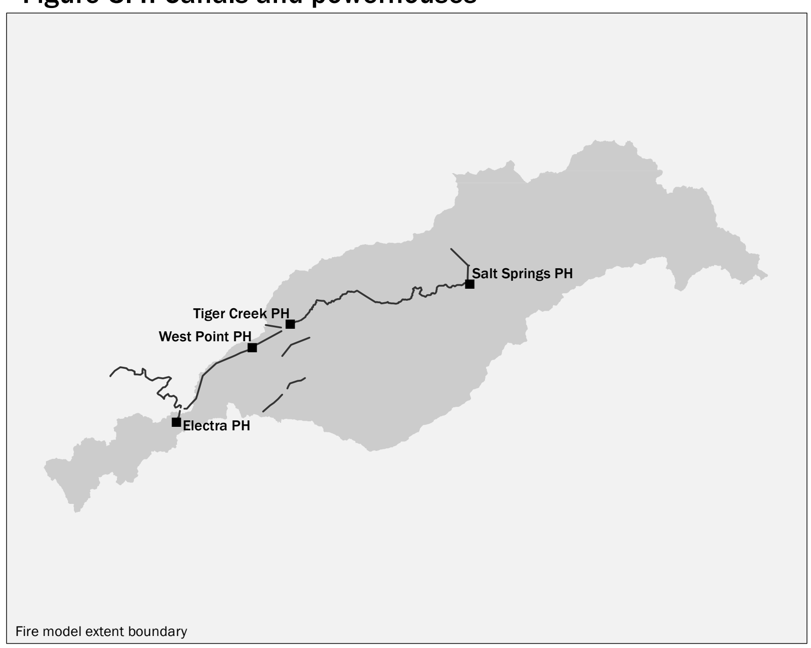
Table 5.5: Miles of canals within the perimeters of the modeled five fires

	Without treatment	*With treatment*	*Difference*	*Percent difference*
Canals (miles)	14.4	9.9	4.5	31%

Source: ECONorthwest, with data from Sierra Nevada Conservancy

Cost estimates for canal damages are difficult because effects could range from hours of staff work to clear debris all the way to major repair and loss of operations. Where landslides and debris flows are likely, dredging could be a potential cost. We discuss potential operational impacts on water and energy supplies in Chapter 6.

Figure 5.4: Canals and powerhouses



Even though utility representatives have reported that they are not strongly concerned that there will be major structural damage to powerhouses or canals from wildfire, if there were damage, costs could be substantial. PG&E has protocols for reducing wildfire risk around major structures and defending them from wildfire. Overall, capital costs for new hydropower projects range from $2,000 to $3,000 per kW of capacity (US Energy Information Administration 2010). Based on PG&E's 234 MW of hydropower capacity in the watershed, the capital replacement cost would therefore range from $470 to $700 million.[2] Electra Powerhouse is the only powerhouse within the fire pretreatment perimeter. No

[2] See detailed utility infrastructure inventory in Chapter 6.

powerhouses are within the posttreatment fire perimeters. No dams overlap with the fire perimeters, with or without fuel treatments. Similar to canals and powerhouses, we discuss operational effects of wildfire, and its aftereffects, on dams in Chapter 6, including the value of changes in their operational capacity.

5.4.1 Roads

A wide variety of road repair and replacement costs can be incurred following wildfire. Roads can be heavily affected by runoff, debris, and sediment, including the removal of logs, the repaving or re-grading of heavily damaged sections, and the repair of drainage structures. The California State Transportation Agency (CalTrans), for example, described the following $2.5 million in damages from a fire in Ventura, and the type of tasks that need to be undertaken to restore function: "The wildfire burned and damaged vegetation, roadway signs and highway fencing. This project is to place guardrail to protect the roadway from post-fire falling rocks and debris flows, protect drainage system, replace damaged roadway signs, replace damaged highway fencing, and repair wire mesh and cable anchored covered hillside" (Keck 2013). Similarly, during the 2003 San Diego Fires, CalTrans suffered approximately $15 million in damages to existing roadways[3] (CAL FIRE 2003). This figure included the costs of maintenance and damage assessment teams, field data collection, and the replacement of roads, guardrails, signage, electrical supply, and culverts. Wildfire can disrupt access to roads, reducing the ability to use infrastructure and access assets. Disruptions such as these are relevant to the discussion of periods of loss of use of utility infrastructure in Chapter 6.

Table 5.6 and Table 5.7 show the miles of road, by jurisdictional entity, that would be exposed to fire under the fire model scenarios, and the potential costs associated with restoring these roads to their prefire conditions. The costs are based on per unit values for general project estimates. These costs are based on near total replacement of costs and are consequently possibly over-estimates, although CalTrans individual project costs for postfire repairs are of similar magnitude.

Table 5.6: The effects of the five fire scenario on roads (miles of roads affected)

	All roads	*Forest service roads*	*State highway 26*	*All other roads (state, county, and private)*
Without treatment	235	153	7	75
With treatment	147	109	2	36
Difference	88	44	5	39
Percent difference	37%	29%	71%	52%

Source: ECONorthwest, with data from ESRI.

[3] The 2003 Cedar Fire in San Diego County burned 1,134 km^2. CAL FIRE. 2003.

Table 5.7: Representative total cost of repairing/replacing affected roads

	Forest service roads	*State highway 26*	*All other roads (state, county, and private)*
Without treatment	$6,894,000	$1,560,000	$14,400,000
With treatment	$4,915,000	$459,000	$6,850,000
Cost per mile	$45,000	$225,000	$192,000

Source: ECONorthwest, with data from multiple sources. See footnote.[4] Based on per unit values and compared to total costs from recent fires in California.

5.5 Power Transmission Lines:

Following the 2003 San Diego fires, San Diego Gas and Electric spent roughly $71.1 million to replace lost equipment and to restore services, which included the repair or replacement of approximately 3,200 power poles, 400 miles of wire, 400 transformers, and more than 100 other pieces of equipment (Rahn 2010). Table 5.8 shows average costs of a new transmission line. Taking the average of these costs ($1.725 million per mile) and assuming that a conservative 10% of the transmission line mileage exposed to fire in the model needs to be replaced, we obtain the results shown in Table 5.9.

Table 5.8: Average cost per mile (2012$)

	New transmission line	*Removal of transmission line*	*Reconducter/upgrade transmission*
60 kV	$1.24-$2.21 million	$0.22-$0.37 million	$1.04-$2.57 million
115 kV	$1.24-$2.21 million	$0.22-$0.37 million	$1.04-$2.57 million
230 kV	$1.45-$2.62 million	$0.40-$0.58 million	$1.25-$3.21 million

Source: California ISO. 2012. *PG&E 2012 Final Per Unit Cost Guide*. Retrieved on April 17, 2013 from www.caiso.com/Documents/ PGE_2012FinalPerUnitCostGuide.xls.

Notes: These costs do not include: (1) engineering costs), (2) capitalized licensing and permitting costs, (3) civil work, (4) general facilities, (5) substation control buildings, (6) incremental cost for transmission line crossings, (7) incremental cost of soil/geotechnical mitigation measures, (8) incremental environmental monitoring and mitigation, (9) corporate overheads, (10) income tax component of contribution.

The assumption of 10% is based on conversations with PG&E and review of expectations by other utilities, based on protocols to treat areas and defend transmission lines during wildfire. This is largely due to the fact that utilities keep transmission line corridors clear of overhanging branches, providing enhanced protection even if the line is within the fire perimeter. For this reason we used a 10% transmission line replacement rate in both our high and low cost estimates in the final results. Under severe fire conditions, however, the damages and subsequent costs could be ten

[4] Forest service road estimates based on the per mile cost of reconstructing existing roads to meet current design standards. The work involved is similar to clearing and reconstructing fire-damaged roads (Krause 2000). County highway reconstruction/upgrade cost: Foth and Van Dyke 2003. Average county road construction cost: Texas 2001.

times these amounts. This was the case in the aforementioned fires in the San Diego area in 2003, which saw a higher rate of damage. If fires in the Mokelumne burn at a higher intensity with a faster rate of spread, a loss of 50% of the transmission line within the fire perimeter is possible, with a resulting replacement cost of $8.0 million dollars.

Table 5.9: Potential transmission line impacts and costs

	Power transmission lines (miles)	Percent of total mileage affected by fire	Mileage affected by fire	Repair/ replacement costs
Without treatment	18	10%	1.81	$3.1 million
With treatment	8	10%	0.85	$1.5 million

Source: ECONorthwest, with data from Sierra Nevada Conservancy.

5.6 Unquantified Land Effects

In this analysis, we do not directly evaluate the natural capital value of ecological structures (e.g., nesting trees, old growth forests) that would be lost in a wildfire, as well as their associated ecological processes and potential goods and services. We also do not evaluate the impact a large wildfire within the watershed may have on jobs and the local communities. Several of our analyses do capture elements of these values, as property and structural values are in part based on the aesthetic, recreational, and even spiritual benefits associated with the Mokelumne ecosystem. Timber values capture a share of the consumptive values. We also discuss erosion and sediment effects (Chapter 6), which are also associated with ecological structures. While we do not describe the value of habitat function nor the associated plant and wildlife species, the effectiveness of the treatments in reducing the fire footprints in our modeled scenario suggests that valuable ecological structures could be protected by the treatments.

Because the results of the modeling are spatial, further analysis can overlay the results on key ecological areas to determine the extent of the treatments' effectiveness. With the onset of climate change and continued ex-urban growth, the scarcity of forest, riparian, and aquatic ecosystems in California will continue to raise the natural capital value and importance of intact ecosystems.

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Chapter 6: Electricity and Water Utilities in the Mokelumne Watershed

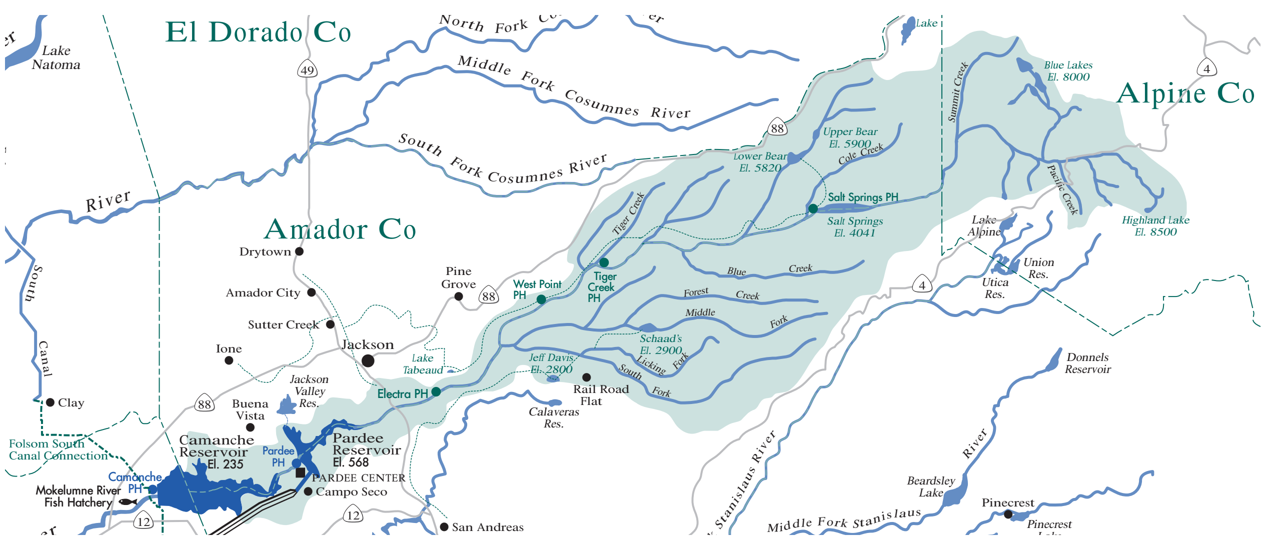
6.1 Context

In this section we use model results to describe the potential effects of the predicted postfire sediment movement in the Mokelumne River on reservoirs in the upper Mokelumne watershed as well as its subsequent effect on utility electricity generation and water supply, including potential costs. Pacific Gas and Electric (PG&E) and East Bay Municipal Utility District (EBMUD) both own and operate land and infrastructure in the Mokelumne watershed, with PG&E operations located upstream of EBMUD. Figure 6.1 shows the location of Pardee and Camanche reservoirs, which are owned and operated by EBMUD, as well as the upstream facilities that belong to PG&E. In addition to PG&E's operations, the Calaveras Public Utility District (CPUD) operates two reservoirs within the watershed (Schaad's and Jeff Davis), and the Amador Water Agency (AWA) operates two diversions. Potential fire/postfire impacts on CPUD and AWA operations were not part of the scope of this study.

PG&E's operations are oriented toward electricity generation, and EBMUD is primarily focused on water supply to its service area. The intricate system of storage, diversion, and conveyance throughout the watershed has allowed these utilities, and other water right holders, to provide reliable power and water to their respective customers.

In this section, we describe how and why reservoir storage capacity is valuable to PG&E and EBMUD. We use this understanding of how and why storage capacity is currently valuable to their operations and objectives to estimate the value of lost storage capacity.

Figure 6.1: Upper Mokelumne utility powerhouses and reservoirs



Source: EBMUD

EBMUD recognizes and acknowledges the importance of reservoir storage capacity in the Mokelumne watershed. In EBMUD's initial 2040 plan from 2009, in addition to investments in water conservation, water recycling, and new supplemental supplies, the District sought to include the potential increase in the Pardee Dam height to increase storage capacity for drought supply purposes. This would have flooded up to 1.4 miles of the upper portion of the river. A coalition successfully contested this plan in court. The revised 2011 plan kept some elements of the 2009 plan, such as water conservation, water recycling, and water transfers, but the revision did not include Pardee Reservoir expansion and instead considered other drought solutions, such as partnering in expanding Los Vaqueros Reservoir, a future expanded Lower Bear Reservoir, groundwater banking in Sacramento and San Joaquin Counties, and desalination.

PG&E representatives report that their organization is not concerned with reservoir sedimentation in the upper Mokelumne watershed, largely due to the fact that the bulk of their storage capacity is upstream of areas contributing sediment. In addition, Tiger Creek Afterbay, which provides storage and depth for diversions, can open gates that allow the flushing of sediment downstream, although federal licensing and state water quality requirements place some restrictions on the timing of such flushes, and an approval process typically takes time. PG&E reports that it has taken precautions to design and manage for fire and debris flows in terms of avoiding direct interruptions to their operations. Direct fire effects and sediment pulses from debris flows or major storms would generate short-term costs and likely interruptions in some operations, particularly if access were compromised. Large storm events can act as a natural flushing mechanism to move sediment and debris downstream from where they originally collect after eroding from the hillside or banks. And flushing sediment does not remove it from the river, but rather sends it downstream. Because of how Pardee Dam is constructed and due to its surrounding geography, it does not have the flushing capability of Tiger Creek Afterbay dam. This leads to a distributional issue in the long run, as sediment makes its way into Pardee Reservoir from the upstream channels and reservoirs.

In the remainder of this chapter, we identify the utility infrastructure in the upper Mokelumne watershed, including its operation and value, and discuss how these operations and values are affected by sediment associated with wildfire. We provide value estimates for the effects on electricity generation and water supply. This includes effects from a variety of scenarios because the utilities have multiple options for responding to sediment loads, such as changing operations, flushing sediment downstream, or dredging sediment.

6.2 Upper Mokelumne Utility Infrastructure

PG&E operates 12 dams and diversions in the upper Mokelumne, with a total initial storage capacity of 273 million cubic meters (Table 6.1). 6.5 million cubic meters of original storage capacity for PG&E is downstream of Salt Springs Reservoir and in the scope area for this study (hereafter referred to as the affected area). EBMUD has two major reservoirs in the affected area, with a total original storage capacity of 790 million cubic meters, nearly three times that of PG&E within the watershed, and more than 100 times the storage capacity in the affected area as PG&E.

Table 6.1: Historic capacity of reservoirs in the upper Mokelumne watershed

Dam name	Owner	Reservoir name	Original capacity (thousand cubic meters)	County	Year com-plete
Lower Blue Lake	PG&E	Lower Blue Lake	5,304	Alpine	1903
Upper Blue Lake	PG&E	Upper Blue Lake	9,251	Alpine	1901
Twin Lake	PG&E	Twin Lake	1,604	Alpine	1901
Meadow Lake	PG&E	Meadow Lake	6,365	Alpine	1903
Bear River	PG&E	Bear River	8,410	Amador	1900
Lower Bear River	PG&E	Lower Bear	60,132	Amador	1952
Salt Springs	PG&E	Salt Springs Reservoir	175,031	Amador	1931
Tiger Creek Regulator	PG&E	Tiger Creek Regulator	645	Amador	1931
Tiger Creek Forebay	PG&E	Tiger Creek Forebay	44	Amador	1931
Tiger Creek Afterbay	PG&E	Tiger Creek Afterbay	4,885	Amador	1931
Electra	PG&E	Electra Diversion	80	Amador	1947
Lake Tabeaud	PG&E	Lake Tabeaud	1,443	Amador	1901
Schaad Lake	CPUD	Schaad Reservoir	1,740	Calaveras	1939
Jeff Davis	CPUD	Jeff Davis Reservoir	1,750	Calaveras	1973
Pardee	EBMUD	Pardee Reservoir	259,031	Amador	1929
Camanche	EBMUD	Camanche Reservoir	530,397	San Joaquin	1963

Source: UC Davis Center for Watershed Sciences. 2013. Hydra.ucdavis.edu.

For electricity generation, PG&E has four powerhouses in the affected area, for a total of 214.5 megawatts (MW) of generation capacity, compared to EBMUD's 34 MW of capacity (Table 6.2). PG&E primarily relies upon precipitation and storage capacity upstream of all four of its powerhouses for its supply. PG&E powerhouses depend mostly on off-channel surface and subsurface conveyance within the affected project area, totaling 54 km in length (Table 6.3).

Table 6.2: Powerhouses in the upper Mokelumne watershed

Dam name	Owner	Year online	Storage reservoir	capacity (MW)
Salt Springs	PG&E	1931	Salt Springs	44
Tiger Creek	PG&E	1931	Tiger Creek Regulator	58
West Point	PG&E	1948	Tiger Creek Afterbay	14.5
Electra	PG&E	1948	Lake Tabeaud	98
Pardee	EBMUD	1930	Pardee	23.6
Camanche	EBMUD	1963	Camanche	10.6

Sources: PG&E and the UC Davis Center for Watershed Sciences. 2013. Hydra.ucdavis.edu.

Table 6.3: PG&E conveyance structures in the upper Mokelumne watershed

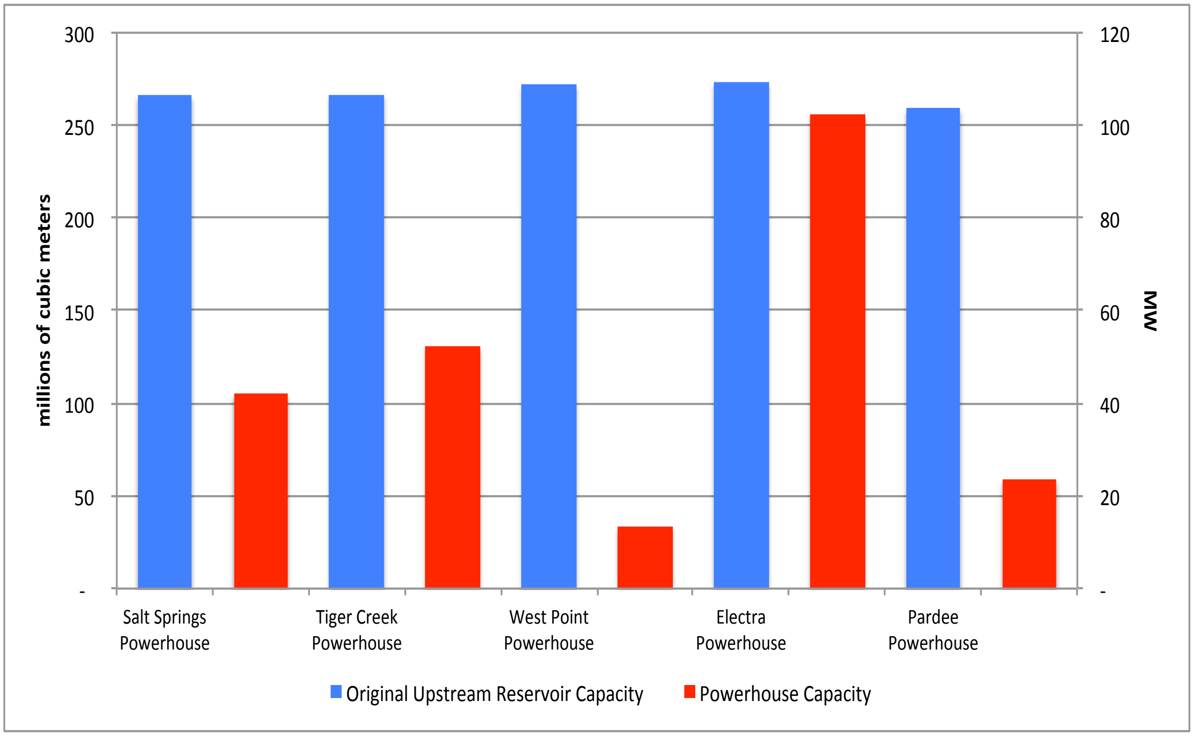
Conveyance	Length (km)	Start-End
Salt Springs Tunnel & Penstock	3.6	Lower Bear Reservoir – Salt Springs Powerhouse[1]
Upper Tiger Creek (canal)	26.6	Salt Springs Powerhouse – Tiger Creek Regulator Reservoir
Tiger Creek (canal)	3.8	Tiger Creek Regulation Reservoir – Tiger Creek Forebay
Tiger Creek Penstock	1.4	Tiger Creek Forebay – Tiger Creek Afterbay
West Point Tunnel & Penstock	4.3	Tiger Creek Afterbay – West Point Powerhouse
Electra Tunnel	13.6	West Point Powerhouse – Lake Tabeaud
Electra Penstock	0.9	Lake Tabeaud – Electra Powerhouse

Source: Foothill Conservancy and UC Davis Center for Watershed Sciences. 2013. Hydra.ucdavis.edu.

Based on the effects of wildfire and fuel treatment described in Chapter 3, we focus our assessment of effects for electricity generation on the four PG&E powerhouses and EBMUD's at Pardee Dam. PG&E and EBMUD do not manage their infrastructure in conjunction (but they do coordinate some operations) and they have different primary objectives (electricity vs. water), consequently we attribute only EBMUD-controlled storage capacity for use in its electricity operations at Pardee (Figure 6.2). Figure 6.2 also demonstrates that PG&E's storage capacity is almost completely contributed by Salt Springs Reservoir and upstream (i.e., upstream reservoir capacity for Electra Powerhouse is the summation of the capacity of reservoirs upstream of the powerhouse – the fact that its capacity only slightly exceeds that of Salt Springs indicates that there is not much storage between Salt Springs Powerhouse and Electra Powerhouse). Consequently, storage located in the affected area can be used for operations and daily management, but it does not make a significant contribution to PG&E's ability to capture peak flows for later use at times of increased generation value.

[1] Salt Springs Powerhouse has two units, one of which is fed via the penstock from Cole Creek and Lower Bear Reservoir, while the other is fed directly from Salt Springs Reservoir through the dam.

Figure 6.2: Powerhouse and original reservoir capacity

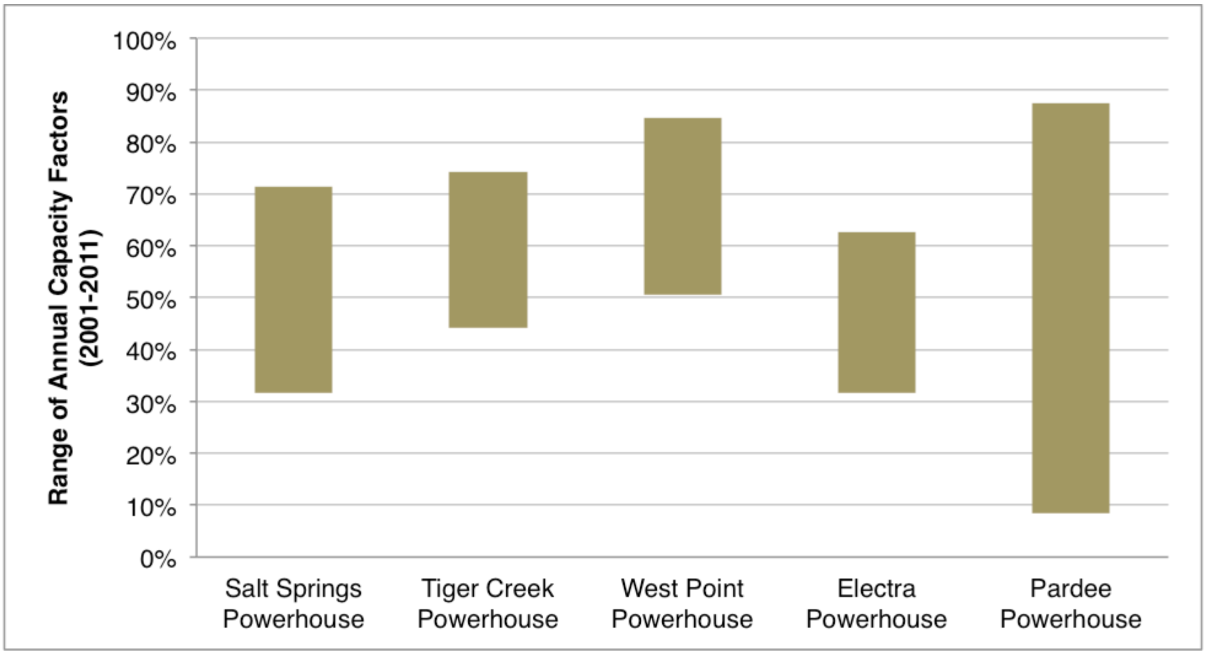


Source: ECONorthwest, with data from UC Davis Center for Watershed Sciences. 2013. Hydra.ucdavis.edu.

6.3 Upper Mokelumne Electricity Operations

The infrastructure described above outlines electricity generation opportunities for PG&E and EBMUD. The U.S. Energy Information Administration (EIA) provides data on the historical operation of these facilities. In Figure 6.3, the annual capacity factor is defined as the amount of electricity a powerhouse generates in a year divided by the amount of electricity that powerhouse could potentially generate over that time period. The difference between potential generation and actual generation is often due to the available water supply to produce energy combined with legal and operational constraints on generation and diversions. For the PG&E powerhouses, the lowest capacity utilization over the decade occurred in 2007 and 2008; for Pardee Powerhouse, the lowest utilization was in 2002. Dry years typically correspond with low utilization and wet years correspond to high utilization, although water availability and capacity factor do not perfectly correlate. All five powerhouses have experienced a wide range of operations, with each experiencing years of 50% or less capacity factor from 2001 to 2011, and none reaching 90% or above in a year. This demonstrates that increased available water supply would generally provide increased energy generation potential throughout the affected system. Other factors in the management of these systems that can lower the capacity factor for a given powerhouse include planned or forced outages and equipment maintenance and upgrades.

Figure 6.3: Annual capacity factors



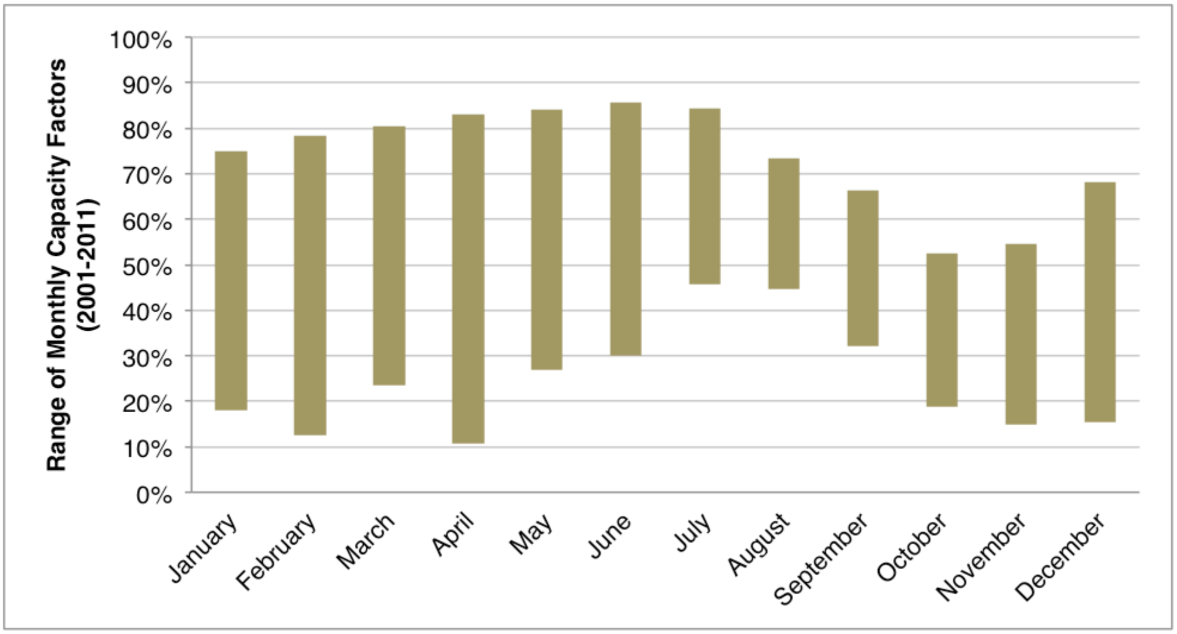
Source: ECONorthwest, with data from U.S. Energy Information Administration. Form EIA-923 Detailed Data. Retrieved from http://www.eia.gov/electricity/data/eia923/index.html. June 2013.

When aggregating the five powerhouses and analyzing the overall monthly energy generation from 2001 to 2011, May through July is the period with the highest utilization (Figure 6.4). Total annual electricity generation for the five powerhouses ranges from 695,000 megawatt hours (MWh) in 2007 to twice that—1.4 million MWh—in 2005 and 2006 (Figure 6.5). The total capacity for generation of these five powerhouses is 2.05 million MWh annually, although late summer water availability and management needs make this level impossible to achieve.

Monthly capacity factors are based on both monthly fluctuations in demand for electricity as well as monthly fluctuations in the available supply of water to generate it. However, it is difficult to directly align market rates and water availability because PG&E manages a complex network of varied electricity sources and faces opportunities to purchase and sell electricity generated outside of California. Alignment attempt are further complicated by the broader California energy market and the California Independent System Operator.

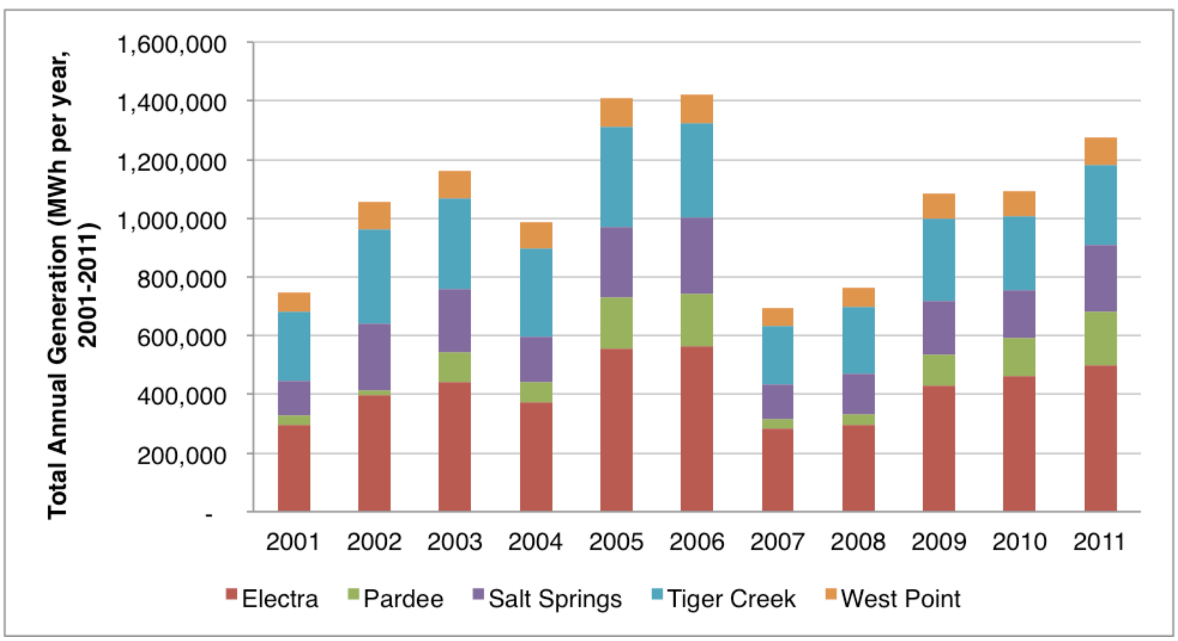
Electra Powerhouse is the largest of the five powerhouses and it consistently generates the most electricity (Figure 6.6). In normal and wet water years, all five powerhouses operate at a high capacity factor from March through June then drop off through the rest of the summer and fall. There is no substantial storage downstream of Salt Spring Reservoir for PG&E; the water flowing out of Salt Springs and its powerhouse is the primary source of water for generation in the subsequent downstream powerhouses that PG&E operates. Therefore, generation across the four PG&E powerhouses generally correlates, although the relatively small diversion and storage opportunities below the Salt Springs powerhouse allow PG&E some flexibility to lag generation downstream to a minor degree. Storage for EBMUD's power generation is largely based on storage within Pardee Reservoir.

Figure 6.4. Monthly capacity factors



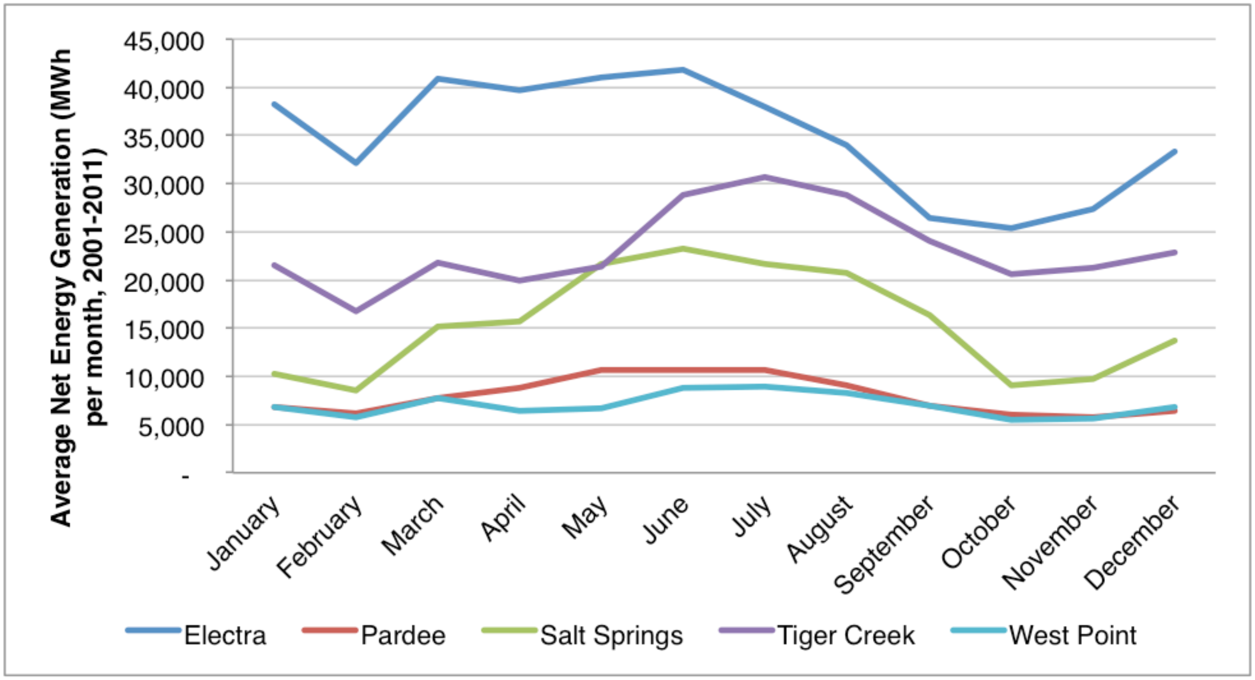
Source: ECONorthwest, with data from U.S. Energy Information Administration. Form EIA-923 Detailed Data. Retrieved from http://www.eia.gov/electricity/data/eia923/index.html. June 2013.

Figure 6.5. Annual electricity generation (of 2.05 million MWh annual capacity)



Note: Dry years: 2001, 2004, 2007, and 2008; below-normal years: 2002, 2003, 2009, and 2010; above-normal years: 2005; wet years: 2006 and 2011.
Source: ECONorthwest, with data from U.S. Energy Information Administration. Form EIA-923 Detailed Data. Retrieved from http://www.eia.gov/electricity/data/eia923/index.html. June 2013.

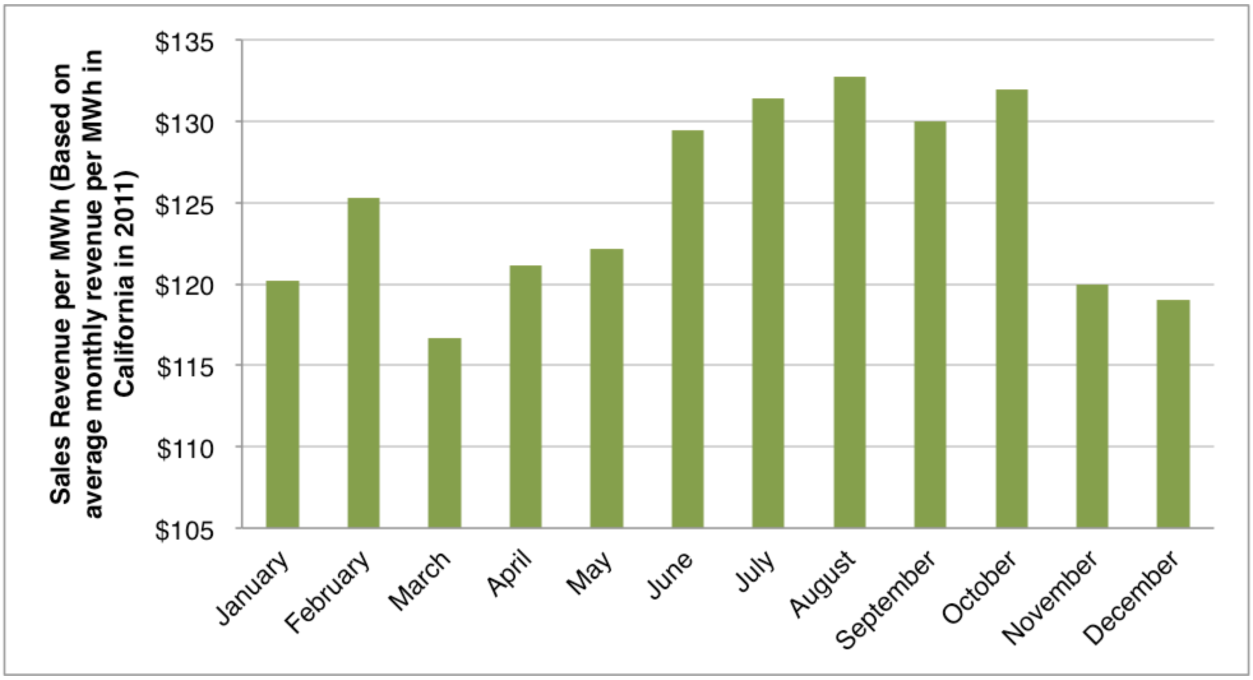
Figure 6.6: Monthly average electricity generation



Source: ECONorthwest, with data from U.S. Energy Information Administration. Form EIA-923 Detailed Data. Retrieved from http://www.eia.gov/electricity/data/eia923/index.html. June 2013.

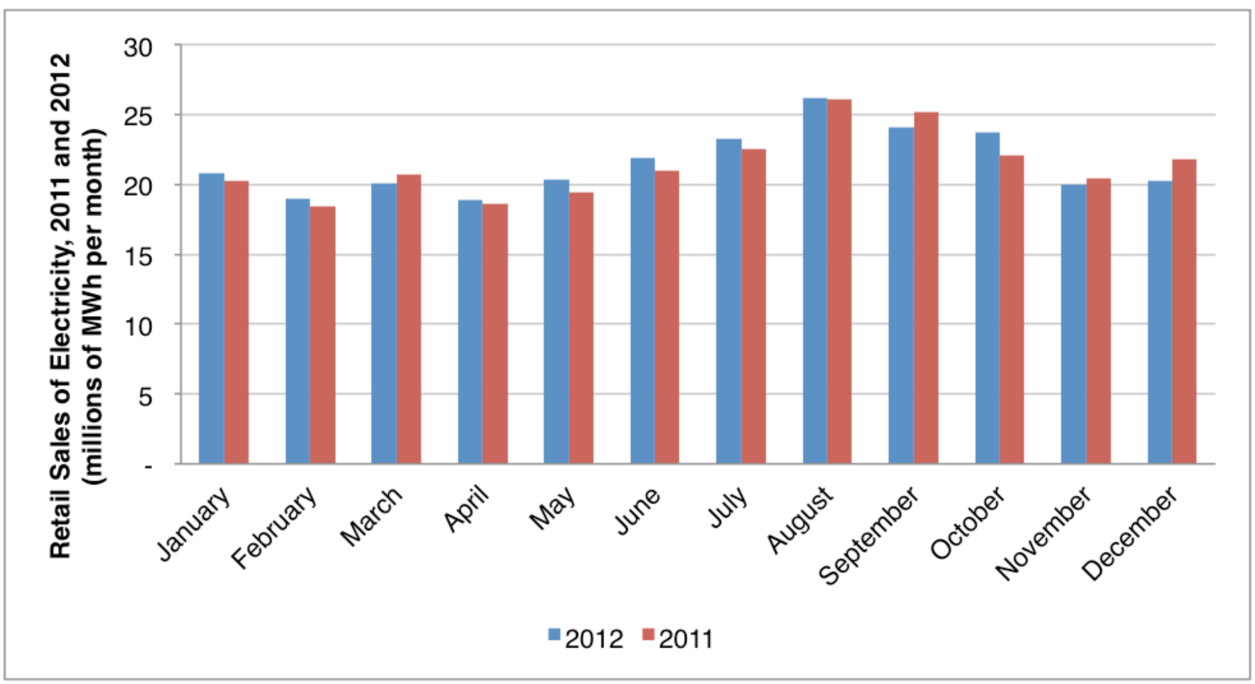
Overall, Figures 6.3 - 6.6 demonstrate that late summer water availability is likely insufficient for the five powerhouses to generate their maximum electricity potential, and in general, they experience peak usage in late spring through early summer. Demand and associated value, however, peak later in summer. After satisfying other regulatory and contractual requirements, PG&E would not be able to as readily address peak energy demand with a reduction in storage capacity. For example, 2011 data on the average monthly sales revenue to electricity generators demonstrates this peak in August, with high demand continuing through October (Figure 6.7). The electricity rate in Figure 6.7 is equal to the monthly sum of all revenue from end users (i.e., ratepayers) in California in 2011, divided by the total amount of electricity they used, in MWh. Similar to the peak in rates or prices, total electricity consumption across all consumers in California peaked in August, followed by September, in 2011 and 2012 (Figure 6.8).

Figure 6.7. Electricity rates by month, 2011



Source: ECONorthwest, with data from U.S. Energy Information Administration. Form EIA-923 Detailed Data. Retrieved from http://www.eia.gov/electricity/data/eia923/index.html. June 2013.

Figure 6.8. Monthly electricity consumption by all sectors in California, 2011 and 2012



Source: ECONorthwest, with data from U.S. Energy Information Administration. 2013. Electric Power Monthly. http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_4_a. Accessed June 2013.

The EIA provides national averages for operating costs by electricity generation technology, but does not include capital costs. For hydroelectric, from 2001 to 2011, the average operating cost per MWh was $4.50 and the average maintenance cost per MWh was $3.16, for total operating expense of $7.67 per MWh (US EIA 2011). These operating costs for electricity generation are substantially below the market sale rate per MWh, particularly at times of highest demand in late summer to early fall. This suggests the importance of these five Mokelumne powerhouses maintaining their current generation output as well as release timing flexibility, especially in the face of an uncertain future of climate change. The predictions for the Sierra Nevada, as we describe in Chapter 9, indicate that natural storage in snowpack will likely decline and the region will likely face a less predictable precipitation pattern. Hydropower provides roughly 15% of electricity generation in California (US EIA 2012).

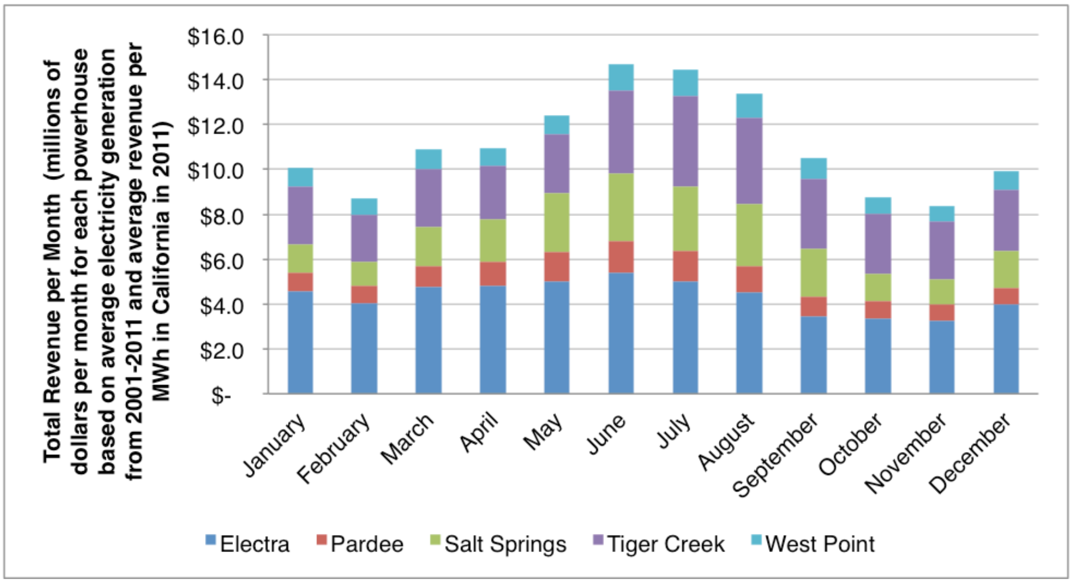
EBMUD's primary goal is water delivery; power generation is towards the bottom of the District's operating priorities. Optimizing for power generation would require moving water through EBMUD's powerhouses and out to Camanche Reservoir, rather than into the aqueduct to the East Bay. EBMUD has obligations below Camanche Reservoir to meet specific cold-water temperature guidelines, which, especially in the middle of summer, can require supplemental cold water from Pardee to Camanche. Once those requirements are met (water delivery to the East Bay and cold downstream water), EBMUD then optimizes for power production to achieve the best price for power sold. In short, EBMUD has very limited ability to modify its current operations and it will not put power revenue above water supply and environmental obligations.

To consider the difference in revenue for PG&E and EBMUD from changes in storage capacity, we must identify how the timing of electricity generation could be affected. In general, the preceding discussion suggests that PG&E and EBMUD generate electricity from the five powerhouses earlier than would be optimal given market demand. Consequently, decreases in storage capacity shift the share of electricity they can generate from late summer to spring and early summer from the water and snowmelt they are unable to store. We assume there is currently sufficient storage capacity and flexibility such that the changes in capacity described in Chapter 3 would not be sufficient to change operations under current precipitation patterns (versus under predicted climate change conditions). However, PG&E and EBMUD are constrained by various operational and environmental requirements associated with their hydropower licenses that constrain their ability to divert and deviate from the natural flow regime.

This analysis considers a 30-year timeframe of costs and benefits, and the climate chapter (9) describes how potential shifts in precipitation patterns, in combination with loss of storage, could affect overall annual generation. For now, however, we consider the difference in revenue over the course of a contemporary year, ignoring operating costs because they would be similar during any season. For this analysis we do not assume that the change in generation would be sufficient to affect rates. But at some scale across the Sierra Nevada, perhaps as a whole, if hydropower generation opportunities at that scale are insufficient during seasonal peaks, other energy sectors would need to fill the gap, likely leading to higher overall prices.

Based on historical generation and rates, monthly revenue from the five powerhouses ranges from roughly $8 million to nearly $15 million (Figure 6.9). Total monthly revenue captures daily peak and off-peak generation. Daily maximum temperature is closely correlated to daily peak demand in California (CEC 2010). The late summer periods with greatest average electricity demand also have the highest daily peaks. Because hydropower plays an important role in satisfying daily peak demand, the differences in monthly averages likely underestimate the seasonal value of storing water for generation during late summer.

Figure 6.9: Average monthly revenue generation by powerhouse



Source: ECONorthwest, with data from U.S. Energy Information Administration described earlier.

These estimates are based on average per-month electricity generation from 2001-2011, as well as monthly estimates of average revenue per MWh in 2011. The per-MWh revenue estimates represent an average of all electricity sales divided by the total MWh sold for each month in the State of California. In the next section we consider how modeled changes in erosion and sediment accumulation, with and without fuel treatment, could affect the ability of PG&E and EBMUD to optimize generation and revenue, where appropriate.

6.4 Sediment Effects on Electricity Generation

Based on the soils of the upper Mokelumne watershed and the reservoirs within it, it is likely that less than 5% of the sediment that reaches a reservoir in this basin would stay suspended in the reservoir's water column and flow out of the dam and further on downstream (US BOR 2006). The sediment delivery ratio discussed in Chapter 3, combined with the roughly 5% pass-through of material downstream, would mean that, of the sediment moving off the hillside, 23.75% would be expected to settle out in the next downstream reservoir. As previously discussed, Tiger Creek Afterbay is equipped with a slucing valve at the bottom of the dam that allows increased flushing of sediment out of the Afterbay. The extent to which PG&E is able to use this valve is regulated by their license and water quality regulations. Pardee Dam has no such valve, and therefore, under current circumstances, approximately 95% of the sediment that enters the reservoir would be expected to stay within it, reducing capacity for water storage.

As we demonstrated in Chapter 3, the Five Fire scenario and the resulting analyses suggest that fuel treatments would decrease the subwatershed erosion and sediment delivered to Tiger Creek Afterbay and Pardee Reservoir. We use the estimates from Table 3.8 to consider the change in storage capacity and overall sediment load with and without fuel treatments for these two key elements of the EBMUD and PG&E operations in the upper Mokelumne watershed. The first year after the fires would see an estimated loss of 21,000 cubic meters of capacity for Tiger Creek Afterbay, and 86,000 cubic meters for Pardee Reservoir (see Chapter 3 for model results and Appendices A-E for the model parameters used). After the 30 years described in the Five Fire scenario, the difference in decreased storage capacity as a result of sediment accumulation could be an estimated 24,000 cubic meters for Tiger Creek Afterbay (Table 6.4) and 102,000 cubic meters for Pardee Reservoir (Table 6.5).

Table 6.4: Tiger Creek Afterbay capacity with and without fuel treatments (cubic meters)

No treatments	Sediment erosion from hillsides	Sediment that reaches the reservoir	Remaining water storage
Year 0	-	-	1,158,974[2]
Year 1	158,790	41,285	1,117,689
Year 2	36,045	9,372	1,108,317
Year 30	277,107	72,048	1,036,269

Treatments	Sediment erosion from hillsides	Sediment that reaches the reservoir	Remaining water storage	Water storage protected by treatments
Year 0	-	-	1,158,974	-
Year 1	78,614	20,440	1,138,534	20,846
Year 2	20,849	5,421	1,133,114	24,797
Year 30	280,313	72,881	1,060,232	23,963

Note: *Water storage protected* identifies the change in sediment effects on reservoir capacity due to fuel treatments. Year 1 refers to the year the fires occur and when most of the sediment erodes. Year 2 sediment erosion is still above background levels (years 3-30), but much less than Year 1. Sediment that reaches the reservoir is calculated by multiplying the sediment erosion from hillsides amount by the Sediment Delivery Ratio (SDR). The slight decrease in storage protected between Year 2 and Year 30 is because the treatments lead to a small increase in background sedimentation over no treatments, therefore in years 3-30 the treatment areas are slightly more erosive. See Table 3.8 for more information.

These 30-year sediment accumulation totals with no treatments represent 11% of current capacity for Tiger Creek Afterbay and 0.098% of current capacity for Pardee Reservoir. If the average family in California uses 192 gallons of water a day, after 30 years the treatments would have protected enough storage to meet the yearly water needs for more than 375 families. The reductions in fuel-treatments-related sediment accumulation in these two reservoirs represent 2.1% for Tiger Creek Afterbay and 0.042% for Pardee Reservoir. Considering the total upstream storage capacity for PG&E's four powerhouses and assuming a 2% loss of storage capacity based on sedimentation rates from calculations following methods by Minear and Kondolf (2009), the loss of capacity with

[2] From bathymetric survey conducted in September, 2013. See Appendix F for more details.

no treatments represents 0.046% of PG&E storage capacity upstream of its four powerhouses. The avoided sedimentation represents 0.009% of PG&E's capacity.

Table 6.5: Pardee Reservoir capacity with and without fuel treatment (cubic meters)

No treatments	Sediment erosion from hillsides	Sediment that reaches the reservoir	Remaining water storage
Year 0	-	-	240,115,856[3]
Year 1	621,462	155,366	239,960,491
Year 2	117,454	29,364	239,931,127
Year 30	202,583	50,646	239,880,481

Treatments	Sediment erosion from hillsides	Sediment that reaches the reservoir	Remaining water storage	Water storage protected by treatments
Year 0	-	-	240,115,856	-
Year 1	278,940	69,735	240,046,121	85,631
Year 2	48,608	12,152	240,033,969	102,842
Year 30	206,448	51,612	239,982,357	101,876

Note: *Water storage protected* identifies the change in sediment effects on reservoir capacity due to fuel treatments. Year 1 refers to the year the fires occur and when most of the sediment erodes. Year 2 sediment erosion is still above background levels (years 3-30), but much less than Year 1. Sediment that reaches the reservoir is calculated by multiplying the sediment erosion from hillsides amount by the Sediment Delivery Ratio (SDR). The slight decrease in storage protected between Year 2 and Year 30 is because the treatments lead to a small increase in background sedimentation over no treatments, therefore in years 3-30 the treatment areas are slightly more erosive. See Table 3.8 for more information.

Based on the bathymetric survey data, the average erosion rate may be higher than our modeling suggests. Our models of hillslope erosion and debris flows did not include channel erosion or chronic sources of sediment, such as roads, which would be a likely source of coarse sediment (bedload) that has accumulated in the reservoirs. The results of the bathymetric survey indicate that over the course of the Afterbay's 82 years of operation, 3,725,615 cubic meters of sediment have accumulated, or 45,434 cubic meters a year. This is significantly higher than the roughly 10,000 cubic meters a year our modeling calculates as background. Naturally, over the course of 82 years, the watershed has seen numerous fires, road failures, and landslides; the 45,434 cubic meters a year is an average that evens out annual variations in erosion. However, if the previous 82 years are any guide to the next 30 years, and there were no change in the percentage of sediment that is flushed from the Afterbay, it would lose all of its capacity in approximately 26 years. Given the number of assumptions inherent in such a projection, along with the number of options PG&E has before them to flush sediment downstream, this scenario is not included in the economic analysis. Instead, it is included here to suggest that operational strategies used during the previous 80 years may need to be adjusted at some point in the next 30 years, and a change in

[3] Based on sedimentation rates calculated from a 1995 bathymetric survey performed by EBMUD, and then applied to the reservoir through 2012 to estimate current capacity.

operations due to sediment loading may have negative consequences to either PGE or EBMUD, or both.

Similarly for Pardee Reservoir, using the bathymetric results from the 1995 survey, which, when averaged over the 66 years from the build date to the survey, indicates an average of 225,183 cubic meters of sediment deposition a year, or a 0.1% yearly loss in capacity. Multiplying out to the end of our 30-year scenario (or 48 years from 1995), results in a 2043 capacity of 233,360,368 cubic meters, or a loss of 25,670,852 cubic meters of water. This is would represent a greater loss in capacity than our current modeling suggests, and EBMUD has fewer operational options to remove sediment from their reservoir than PG&E does on Tiger Creek Afterbay.

While it is evident that Tiger Creek Afterbay doesn't play an important overall role in storage, it does play a role in the operation of West Point Powerhouse. A short-term loss of use of Tiger Creek Afterbay could threaten the short-term ability to use West Point Powerhouse and its associated electricity and revenue generation. This would likely fall within the scope of PG&E's standard Winter Operating Plan, which calls for the shutdown of powerhouses during high-flow events to protect their infrastructure. Such an outage would last a few hours or days and usually occurs during low-demand periods where the loss in generation is therefore negligible. With a diversion at West Point Powerhouse, Electra Powerhouse can continue to generate electricity without the use of water from the Tiger Creek Afterbay diversion, capturing the water that is released through the Tiger Creek Dam.

From May 1st through June 15th (with a potential extension to July 4th), the Mokelumne Environmental Resource Committee (ERC), that oversees compliance with PG&E's Federal Energy Regulatory Commission (FERC) license, has agreed to provide recreational boating flows from Tiger Creek Afterbay for the Tiger Creek Dam Run on the weekends. Should the water storage capacity in Tiger Creek Afterbay diminish below a certain level, PG&E may be unable to meet its FERC license requirement to supply boating water flow rates for the Tiger Creek Dam Run. This would likely manifest in the inability to provide boating flows on consecutive days in a row, and would therefore affect the recreational use of the river. At such time, PG&E would either need to adjust operations to meet the boating flow requirements, which could affect generation, or be out of compliance on its FERC license.

The percentages of overall change in storage capacity are relatively low. We use them below to estimate effects on energy generation. First though, we consider the costs of dredging these sediment volumes. Later, we use them to consider the value of lost water storage for municipal water supply.

6.5 Sediment Dredging Costs

One of the few options available to PG&E and EBMUD to reclaim storage in their reservoirs would be to dredge the sediment. PG&E reports that they rarely use sediment dredging across their full range of California operations and that they have not conducted sediment dredging in the Mokelumne watershed. They have made clear that they have no expectations of conducting dredging there in the future. Still, dredging projects have recently been necessary for a number of reasons in California, as it is the only option for sediment management under some circumstances. We consider here what the costs of dredging would be but we are not suggesting that sediment dredging would be the most appropriate sediment management strategy. Rather, it is to provide context on other options to manage sediment in the upper Mokelumne. It also provides perspective on the potential cost of an unprecedented scenario that could require dredging to deal with a blockage or fouling of infrastructure, or if sediment loads eventually surpass a threshold in receiving bodies where they cannot be managed by other means.

A recent review of potential actions for ecosystem management in the Sacramento-San Joaquin Delta used an estimate of $6.50 per cubic meter for dredging costs (Medellin-Azuara et al. 2013). As part of the Klamath Hydroelectric Settlement Agreement, parties have investigated sediment-dredging costs for dams on the Klamath River, finding that removing 5 million cubic meters of deposited sediment would cost $97 million, or $20/cubic meter (Wright 2011). Additionally, they calculate that design engineering, construction oversight, legal fees, land fees for deposition, and similar actions would add an additional 25-35% in costs, bringing the full cost of dredging to roughly $26/cubic meter.

Assuming a dredging cost of $26/cubic meter, hypothetical dredging activities equate to a year 1 dredging cost for Pardee Reservoir under the no-treatment scenario of $4.1 million and for Tiger Creek Afterbay of $1.1 million (Table 6.6). This calculation assumes complete dredging of the volume of sediment that would have been avoided with fuel treatments (treatment difference in Table 6.4 - 5). If the true dredging cost of these reservoirs differs from our estimates, the changes would relate to the undiscounted costs in a 1-to-1 ratio (e.g., doubling the per unit dredging cost would double these total dredging cost estimates). Under a 30-year scenario of dredging expenses, the net present value of avoided dredging costs today would be $0.6 million for Tiger Creek Afterbay and $2.6 million for Pardee Reservoir.

Similar to other Sierra Nevada watersheds, the Mokelumne watershed has a history of gold mining, which used mercury as a tool to extract gold. In many Sierra reservoirs, this has led to the deposition of mercury in their sediment, which can complicate dredging. Plans to remove mercury-laden sediment from Combie Reservoir on the Bear River in the central Sierra Nevada call for $6.9 million of funding to remove 46,000-92,000 cubic meters of sediment containing 23 to 68 kilograms of mercury (Nevada Irrigation District 2011). This equates to $75-149/cubic meter, although more recent project descriptions suggest a goal of 153,000 cubic meters of sediment removal, which would equate, if costs don't similarly increase, to a cost of $45/cubic meter (Nevada Irrigation District 2012). Pardee Reservoir has been listed by the State of California as a 303d impaired waterbody due to mercury presence,[4] so the higher dredging costs are likely to apply there. To our knowledge, the sediment of Tiger Creek Afterbay has not been tested for the presence of mercury, although the fact that another reservoir downstream of it has been listed suggests that mercury is present in the watershed.

[4] http://www.waterboards.ca.gov/water_issues/programs/mercury/reservoirs/

If Mokelumne watershed sediment dredging costs turn out to be closer in cost to those of Combie Reservoir dredging costs, due to contamination from past mining operations, the undiscounted results would correspondingly increase. For example, at a dredging cost of $125/cubic meter, the first-year dredging cost would be $2.6 million for Tiger Creek Afterbay and $11 million for Pardee Reservoir.

Table 6.6: Sediment dredging costs ($ millions)

Reservoir, subwatershed		Year 1	Year 2	Year 30 total (undiscounted)	Year 30 total (discounted 3%)
Tiger Creek Afterbay	No treatment	$1.1	$0.2	$3.2	$2.5
	Treatment	$0.5	$0.1	$2.6	$1.9
	Difference	$0.5	$0.1	$0.6	$0.6
Pardee	No treatment	$4.1	$0.8	$6.2	$5.5
	Treatment	$1.8	$0.3	$3.5	$2.9
	Difference	$2.2	$0.5	$2.7	$2.6

Note: these costs are not included in final benefit compilation (conclusion) but rather are used for consideration and comparison.

6.6 Electricity Generation Costs of Fire and Sediment

Electricity generation in the upper Mokelumne can potentially be affected by fire in many ways. Wildfire can make it unsafe to operate transmission lines and therefore require that powerhouses be shut down for brief periods, and it can make powerhouses inaccessible by staff during and immediately following fire. Wildfire can lead to burn debris, landslides, and erosion fouling or damaging transmission, water conveyance, and other infrastructure. Also, flume structures have been damaged and require repair. PG&E reports that they coordinate closely with wildfire incident command teams to manage electricity generation and transmission infrastructure during wildfire events in ways that cause the shortest possible periods of disruption in operation.

Conversations with PG&E staff suggest that they do not expect significant disruptions in electricity generation due to sediment, and they do not expect loss of generation capacity or flexibility. We include the discussion in this section to consider the scale of risk associated with wildfire-based sediment effects in the project area for utilities. We do not include these calculations in the benefit/avoid cost results for the conclusion.

As a first consideration if no dredging occurs: there will be a loss of capacity for Pardee Reservoir and Tiger Creek Afterbay, although the true accumulation of sediment in the Afterbay would depend on flushing rates. If PG&E chooses to flush the sediment downstream via the sluicing valve, or if sediment is naturally flushed downstream during storm events, some percentage of it would eventually settle out into Pardee Reservoir. Consequently, the allocations of costs for electricity generation are somewhat a distributional issue, because if the sediment is flushed downstream, the costs shift to EBMUD as lost storage for municipal water supply. For this analysis, we assume any effect of sediment transported to Tiger Creek Afterbay would be experienced by PG&E operations in terms of storage capacity. In practice it might occur in the form of delays and loss of use for West Point powerhouse, as well as increased operation expenses as we discuss later.

Loss of storage capacity in a hydropower system would force a utility to generate electricity based solely on when water is available (natural runoff) rather than when value for that electricity is at its highest. Peak runoff for the Mokelumne is typically April through May. Therefore, if storage capacity is impacted by sediment deposition, it could force a proportional shift of electricity generation from the optimal time of generation based on demand and market rates (August) to the months of lower overall electricity value for hydropower during runoff (April & May). Utilizing 2011 sales revenue per MWh (Figure 6.7), the difference in revenue from electricity generated during April versus August would equate to 9% less revenue per MWh. We therefore estimate that the portion of water that cannot be stored because of lost storage capacity must be sold for 9% less revenue.

PG&E is able to manage storage capacity for powerhouses primarily via Salt Springs Reservoir, upstream of the affected area. EBMUD manages water in Pardee Reservoir primarily for water supply; electricity generation is a lesser priority. For future consideration and study, but not for inclusion in our the final benefit/avoided cost compilation, we take the share of lost storage to PG&E and EBMUD due to the Five Fire Scenario and assume it would lead to a proportional share of electricity generation that would experience the 9% decrease in revenue as discussed above. Therefore, we take the total revenue generated by both PG&E and EBMUD, multiply this by the share of storage capacity lost to sediment, and multiply this amount by 91% to identify the reduced revenue amount. We do this for each year, as the loss of storage capacity continues to have cumulative effects. It is important to focus on the difference in revenue with and without treatment to net out operating costs. We use data supporting Figure 6.9, with average annual generation from 2001 to 2011, and 2011 rates. We use revenue for Electra and West Point powerhouses for PG&E, and Pardee for EBMUD. Based on these data, average annual revenue for PG&E would be $63 million and $12 million for EBMUD, from the affected powerhouses.

The magnitude of the value of lost potential for peak electricity generation corresponds to the small share of storage capacity affected by the modeled sediment influx (Table 6.7). The 30-year undiscounted (total) preserved revenue generation potential for PG&E from the treatment scenario would be $157,000, or $103,000 at a 3% discount rate. The corresponding amounts are $139,100 and $90,700, respectively, for EBMUD.

Table 6.7: Gross revenue from electricity generation lost due to sedimentation ($ thousands)

Utility		Year 1	Year 2	Year 30 total (undiscounted)	Year 30 total (discounted 3%)
PG&E	No treatment	$8.9	$10.9	$551.6	$336.1
	Treatment	$4.4	$5.6	$394.4	$233.4
	Difference	$4.5	$5.4	$157.1	$102.7
EBMUD	No treatment	$7.1	$8.4	$284.6	$182.0
	Treatment	$3.2	$3.7	$145.4	$91.3
	Difference	$3.9	$4.7	$139.1	$90.7

Note: these costs are not included in final benefit compilation (conclusion) but rather are used for consideration and comparison.

This analysis assumes that the same total annual amount of electricity would be generated with lost storage capacity, because monthly capacity factors demonstrate substantial excess capacity, particularly during spring. If utilities reach their storage limits and are at maximum generation capacity, reduced storage would then equate to loss of generation for the corresponding volume, rather than generation at a time of lower rates.

Another point of relevance is the role of Tiger Creek Afterbay as the primary intake source for West Point Powerhouse and Electra Powerhouses. As such increased sedimentation in the Afterbay could eventually lead to a loss of ability to operate the water intakes that supply those powerhouses, at least for temporary periods. This especially pertains to West Point Powerhouse, as Electra Powerhouse does have the ability to divert instream flows for power generation. The monthly average revenue from 2001 to 2011 for the downstream PG&E powerhouses ranged from $3.3 to 5.4 million a month for Electra and $0.7 to 1.2 million for West Point. Taking these operations offline for a month of maintenance could mean the loss of millions of dollars in generation potential.

More broadly, fire occurrence as described in our Five Fire scenario can cause generation downtime of powerhouses in the vicinity, including Tiger Creek ($2.1 to $4.0 million per month) and Salt Springs ($1.1 to $3.0 million per month) powerhouses. This might manifest via direct fire damage or shutdown, interruption in access or conveyance, or other fire management interruptions. It is difficult to predict a likely scenario, and therefore the potential effect of fuel treatments on that outcome, but the modeled fire intensity along the access roads to those facilities demonstrate the potential danger from fire to block ingress to the facilities. Land managers and fire suppression representatives do report the greater capacity to defend infrastructure and manage wildfire behavior after treatment, so treatments offer a real potential to prevent or greatly reduce future fire-related interruptions. At the extreme, the monthly revenue ranges from $8 to $13 million per month for the four PG&E powerhouses, and $0.7 to 1.4 million for Pardee Powerhouse.

Based on the downstream geography of West Point and Electra Powerhouses and their potential to experience the widest range of these identifiable wildfire effects, we use the minimum value of their combined monthly generation value to represent the order of magnitude value for disruption in generation, which is $4 million. But a wide range of scenarios could cause this value to vary from thousands of dollars to tens of millions, depending on the length and cause of the outage.

6.7 Water Supply Effects

In this section we estimate the annual and cumulative value of lost storage capacity for water supply. While lost storage capacity for electricity generation in the Mokelumne translates to earlier generation at lower rates, a loss of storage capacity for a municipal water supply equates to a loss of capacity to store water during peak flows. All else in the system being equal, this would lead to a need for supplemental water sources to make up for the lost volume. Please refer to section 6.1 for how EBMUD has planned to meet its customers' needs. As described in their Water Supply Management Program, the options they have outlined may not be as cost effective per acre-foot as protecting the storage systems that are currently in place. This is especially true when compared to new surface storage options, as the best sites have already been used, and political pressure against new surface storage can increase planning costs or prevent implementation. This is why protecting existing sources of water from capacity reduction is important.

Studies continue to conclude that conservation provides the most cost effective option for increasing available water in California, particularly in agriculture.[5] A 2010 study by the Pacific Institute found agriculture irrigation efficiency in California could conserve water at a cost of $43 to $391 per acre-foot, an average of $185 per acre-foot (Cooley et al 2010). The Pacific Institute study also found that proposed new reservoirs for agriculture would have cost between $520 and $720 per acre-foot. Separately, a 2009 study by a team of California water experts found that new surface storage costs range from $350 to $1,070 per acre-foot, while desalination ranges from $500 to $2,500 per acre-foot (Hanak et al. 2009). This study found groundwater storage opportunities range from $10 to $600 per acre-foot, and they found agricultural water transfer prices range from $50 to $550 per acre-foot. Prices for water transferred between agricultural users in California are typically much lower than prices municipalities in California pay in times of water shortage. However, rural to urban water transfers often face strong opposition from rural communities and consequently are rare (Hanak et al. 2012), although EBMUD reached three such agreements in 2013.

Based on current available opportunities to increase water supply in the San Francisco Bay area, we conservatively assume a cost of $500 per acre-foot of water in terms of value of storage capacity in the upper Mokelumne watershed.[6]

[5] See the latest California Water Action Plan: http://resources.ca.gov/california_water_action_plan/

[6] EBMUD's Water Supply Management Program 2040 Plan identifies a range of new supply options that range from $400 to $6,100 per acre-foot, with the majority being recycled sources. This suggests that costs of replacing water supply in the future could be substantially more than $500 per acre-foot. Source: EBMUD, 2012. Water Supply Management Program 2040 Plan. http://www.ebmud.com/sites/default/files/pdfs/wsmp-2040-revised-final-plan.pdf.

The 30-year undiscounted value of water supply for Pardee that is able to be stored because fuel treatments reduce fire footprint and severity is worth $1.2 million undiscounted, or $807,000 discounted (Table 6.8). The corresponding value from maintained capacity at Tiger Creek Afterbay is $295,000 undiscounted and $193,000 discounted. At higher replacement water supply costs, the undiscounted costs would proportionally increase, such as a $1,000 per acre-foot cost would equate to a $2.5 million cost for EBMUD as a result of lost Pardee Reservoir capacity.

Table 6.8: Value of water supply protected from sedimentation by fuel treatment ($ thousands)

Reservoir, subwatershed		Year 1	Year 2	Year 30 total (undiscounted)	Year 30 total (discounted 3%)
Tiger Creek Afterbay	No treatment	$16.7	$20.5	$1,035.7	$631.1
	Treatment	$8.3	$10.5	$740.7	$438.3
	Difference	$8.4	$10.1	$295.0	$192.8
Pardee	No treatment	$63.0	$74.9	$2,532.2	$1,619.5
	Treatment	$28.3	$33.2	$1,294.2	$812.2
	Difference	$34.7	$41.7	$1,238.0	$807.2

Note: Value is based on the assumption that replacement water would cost $500 per acre-foot. Years 1 and 2 presume higher than baseline sedimentation due fire, as predicted by the models. Years 3-30 would have baseline erosion rates.

6.8 Summary of Sediment Impacts on Utilities

In this section we consider how a range of possible effects that sediment deposition could affect utility operations in the Mokelumne, and how utilities might need to adjust their operations or actively address sedimentation. Because Salt Springs Reservoir is the primary water source for all of PG&E's hydropower facilities, storage capacity in Tiger Creek Afterbay is of low importance for PG&E as a share of overall storage capacity for the downstream powerhouses. Tiger Creek Afterbay capacity can play a role, however, in terms of uninterrupted operation of the downstream powerhouses, particularly as it relates to meeting its FERC obligations. PG&E has options for flushing sediment (deliberately or naturally), although the frequency and speed with which PG&E could arrange flushing events is somewhat ambiguous. Flushing also means that the sediment is released downstream and would in some proportion affect EBMUD's storage capacity in Pardee Reservoir. Still, the sediment does pose a risk to disrupt electricity generation and can reduce storage capacity, which affects the ability to use hydropower to meet demand.

Effects on Pardee Reservoir are not high in terms of a total share of storage capacity, but EBMUD has frequently demonstrated a desire to seek out solutions to dry year water scarcity, as discussed in its 2040 water plan. Dredging the sediment that would have been avoided with fuel treatment would cost $2.6 million or more over 30 years (discounted). The cost of replacing the lost water storage and resulting supply opportunities would cost EBMUD $800,000 or more over 30 years. Based on the risk that contaminated sediment could dramatically increase dredging costs, combined with the difficulty of securing alternative water supplies, the estimated dredging or water supply costs could reasonably double in cost. These costs could lead EBMUD to other supply sources, such as water transfers, groundwater banking, or increased use of their Sacramento River intake, all of which would come with their own costs. Under the fire conditions modeled in this analysis, treatments are predicted to reduce the rate of sedimentation in Pardee Reservoir, which would postpone the need to act on any of these alternatives.

Sediment dynamics, their impacts on local infrastructure, and how they could affect standing requirements within the watershed (e.g., FERC license), could not be fully assessed at the time of this report. As such, this chapter offers some perspectives on future impacts that could result from incidents in the watershed that have occurred in other areas (e.g., Denver and Rim Fire), but these numbers are not included in the final results because their accuracy need further review. The sediment impacts quantified for the avoided costs in this analysis are the $1 million in discounted, 30-year water supply protected by the treatments for Pardee Reservoir.

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Chapter 7: Treatment Costs and Impacts — Timber and Biomass

7.1 Introduction

In this chapter, we describe the fuel treatments scenario used to rerun the fire model to determine the effectiveness of modeled fuel treatments in the Mokelumne watershed. We apply typical fuel treatments implementation costs by treatment type and the land type where the treatment is placed, for the full implementation of the modeled treatments. Implementation costs are based on information provided by federal and local land managers in the Mokelumne watershed, with review and verification from published literature on fuel treatment costs. We also describe a scaled back approach to the full 100% coverage suggested by the model, based on the methods for fuel treatments used by local land managers and locals familiar with the use of fuel treatments within the watershed, including the Bureau of Land Management (BLM), U.S. Forest Service (USFS), Amador Fire Safe Council, and the Calaveras Foothills Fire Safe Council. We use scaled-back treatment percentages to give a secondary estimate of the costs of treatments according to treatment densities employed by locals in past projects, which are less than 100% of total land cover for an area. Because the level of resolution for our modeling utilizes full treatment (100% of area), and therefore we do not have modeling data to determine the modeled effectiveness of a scaled-back approach, we provide both costs in this chapter.

7.2 Treatment Scenario

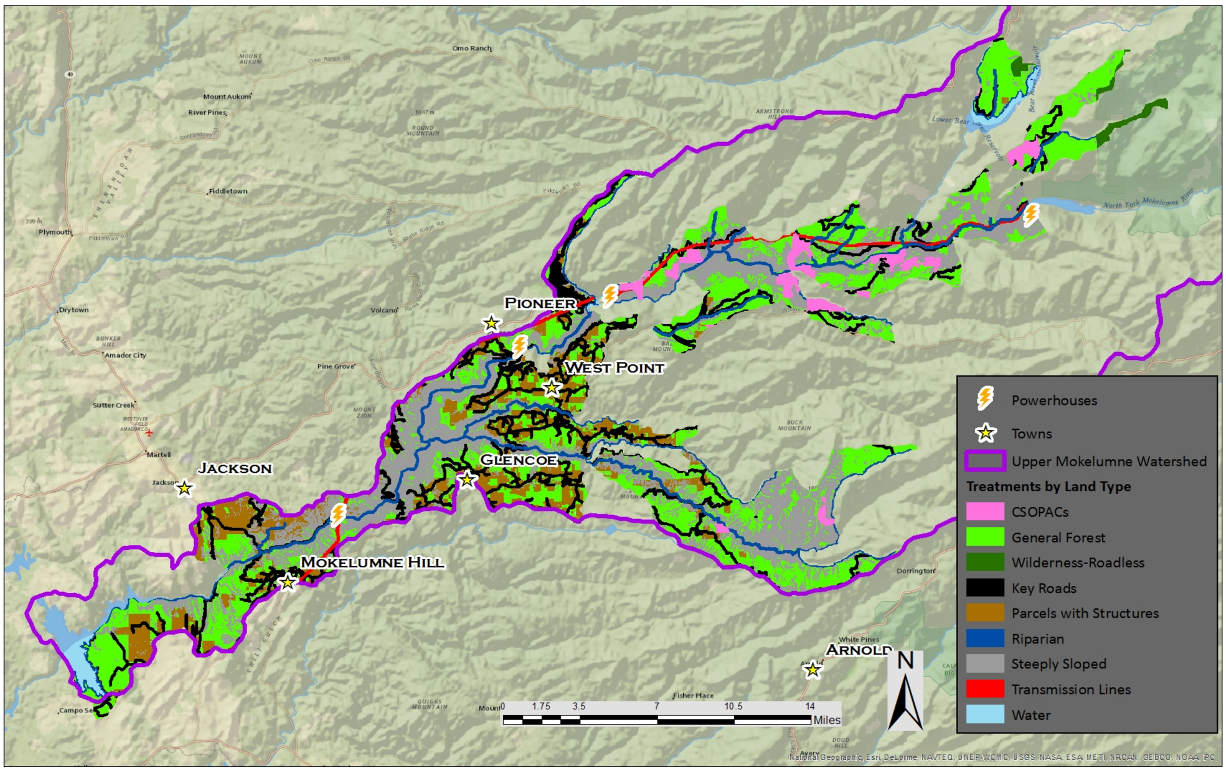
The Committee assigned with the task of designing the treatment scenario developed a treatment matrix to help identify specific treatment strategies for specific portions of the study area (see Table 7.1, or Chapter 2 for more information). Each treatment code corresponds to a specific treatment type, level of overall treatment, and level of canopy treatment, which are the required inputs for the fire model we used for this analysis (Appendix A). The committee then assigned specific treatment codes to Analysis Units (AUs) in the study area, and summarized the treatment scenario spatially in GIS.

The treatment scenario in Figure 7.1 and Table 7.2 assumes 100% treatment of the area for the treated AUs, or rather that within an AU every acre has been treated. In a later section, we discuss the implications from interviews with local land managers, based on their expert opinion and local knowledge, on the actual percentage of an AU that likely needs to be treated to achieve the desired treatment effect.

Table 7.1: Treatment code matrix

	Treatment type	*Level of treatment*	*Level of canopy treatment*
	100 = Wildfire and prescribed burn	10 = Low under burns, light thinning	1 = Low, light under burns, piling of existing surface fuels
Land type	200 = Mechanical mastication, lop & scatter, piling	20 = Moderate, mixed severity burns, moderate thinning	2 = GTR 220 type treatment
	300 = Mechanical timber harvest or biomass removal	30 = Stand replacing burns, clearcuts, seed tree	3 = Shaded fuel breaks, wildland-urban interface treatments

Figure 7.1: Map of treatment scenario



7.3 Costs, Revenues, and Impacts of Fuel Treatments

In this section, we discuss the costs, revenue, and economic impacts associated with fuel treatments in the study area, as identified and designed by the committees. As described in Chapter 2, the treatment scenario relies on several different treatment strategies (e.g., prescribed burns, mechanical harvest) on different land types. The committees considered the hazards and benefits associated with each of these treatment strategies and the locations they are applied to when developing the overall treatment scenario. This section has four parts. First, we discuss the costs of fuel treatments. Second, we discuss potential revenue of timber and biomass harvested during treatment. Third, we discuss how revenues and costs would change over time. Finally, we provide a brief discussion of the economic activity potentially supported by the modeled fuel treatments efforts.

7.3.1 Costs of Fuel Treatments

As previously described, during the development of the treatment scenario, the committees considered the potential hazards from fire and how implementing different treatment strategies might affect fire behavior. In section 7.7, we provide a literature review that informed our cost estimates for the treatment scenario. We also asked BLM, USFS, and local fire district representatives to review our cost estimates based on their experience implementing fuel treatments in the Mokelumne watershed. They also provided us with estimates of fuel retreatment requirements over time.

Table 7.2 summarizes the treatment scenario and aligns each treatment strategy with its potential costs based on local fuel treatment experience, augmented with literature review. These costs represent the initial treatment cost, but not total treatment cost over some time period (see section 7.5). The range in costs reflects a combination of literature-based estimates combined with estimates from local land managers as described above. Because the fire model was run at 100% treatment coverage of land in each AU, the literature review-based costs listed in Table 7.2 are based on 100% treatment of the AUs. In reality, local land managers report that not every acre needs to be physically treated for an area to be more resilient against fire, based on their experience. In Table 7.3, we contrast the cost implications for full treatment of an AU with the costs associated with an effective percentage of treatments, as described by locals.

Table 7.2: Treatment summary and costs

Land Type	*Treatment code*	*Total acres*	*Treatment cost ($/acre)*	*Total cost (millions)*
CSO PAC	111	3,076	$200–$390	$0.6–$1.2
General forest	322	30,740	$130–$1,100	$3.8–$35
Key roads	323	15,946	$300–$1,800	$4.7–$29
Parcels with structures	323	10,039	$300–$1,800	$3.0–$18
Riparian	311	7,542	$130–$1000	$0.9–$7.5
Steeply sloped	322	30,121	$130–$2,200	$60.9–$67.8
Transmission lines	323	1,557	$300–$1,800	$1.9–$2.8
Wilderness-roadless	111	873	$300–$900	$0.3
Total	*N/A*	*99,894*	*$130–$2,200*	*$17–$160*

Note: CSOPAC = California spotted owl protected activity centers.
Source: Input from William Haigh, BLM, and review by other local land managers, with literature review for verification. See 7.7 for the literature details.

7.3.1.1 Alignment with typical treatment coverage in the area

In total, the modeled treatment scenario covers nearly 100,000 acres and implementing this scenario would cost between $17 and $161 million. For the fire modeling conditions and to minimize the number of assumptions that are made, we must assume the entire treatment scenario is completed in one year. In section 7.5, we show cost estimates for a treatment process over time that is more realistic. To refine the cost estimate, we align the treatment types and coverage with costs for recent and ongoing fuel treatment projects in the Mokelumne, which results in an estimate of $46 million, not including treatment maintenance costs later down the road (Table 7.3). Based on estimates by type of treatment and land type with appropriate share of total area treated, locals estimate that an actual strategy to achieve fire-resiliency results comparable with our modeled treatment scenario would cost $16 million.

Table 7.3: Treatment costs and coverage based on local feedback

Land type	*Local treatment cost ($/acre)*	*Total cost (100% treatment)*	*Share of land treated*	*Total cost (reduced coverage)*
CSOPACs	$250	$770,000	30%	$230,000
General forest	$210	$6,500,000	40%	$2,600,000
Key roads	$1000	$16,000,000	50%	$8,000,000
Parcels with structures	$1000	$10,000,000	10%	$1,000,000
Riparian	$700	$5,300,000	30%	$1,600,000
Steeply sloped	$210	$6,400,000	40%	$2,600,000
Transmission lines	$430	$660,000	40%	$260,000
Wilderness-roadless	$250	$220,000	40%	$87,000
Total		*$46,000,000*		*$16,000,000*

Source: ECONorthwest with input data from W. Haigh, BLM. Data rounded to 2 significant digits.

7.3.2 Factors influencing costs

In general, the costs of fuel treatments are site specific, therefore estimating an overall cost for the modeled treatment scenario is difficult. Among the factors that play an important role in determining treatment costs are: (1) public vs. private land, (2) inclusion of biomass collection efforts, (3) treatment method (e.g., prescribed fire, thinning, harvest), (4) harvest method (e.g., mechanical, manual), (5) topography and location (e.g., steep slope, WUI, riparian), and (6) proximity to roads. In some cases, a single factor can double treatment costs for a particular area (e.g., biomass collection efforts). Given the large and diverse area included in the modeled treatment scenario, the range of costs included in this analysis likely reflects the correct order of magnitude of potential costs of fuel treatments. It is important to point out that the costs portrayed here, for the most part, likely only capture a portion of the planning costs of implementing the treatments on the ground. Planning costs are highly variable, agency-specific, and intermingled with other efforts and staff responsibilities. Consequently, planning costs are not typically included in fuel treatment cost estimates from the literature for these stated reasons (e.g., Calkin 2006).[1]

7.4 Revenues from Fuel Treatments

The modeled treatment scenario has the capacity to generate revenue in two ways: (1) the merchantable timber removed in timber harvests can be sold to local mills, and (2) the biomass

[1] Note: We did request planning costs for inclusion in treatment cost estimates, but information is not readily available to fully estimate all planning costs at this scale of treatment implementation by agency staff.

collected can be sold to local facilities for value-added products, such as to generate electricity, as bedding for animals, or as landscaping materials. In order to quantify the potential value of these revenue sources, we must make several assumptions regarding the volume of each forest product collected for each of the modeled fuel treatments, as well as the average value of the forest products on the market.

7.4.1 Total available volume

To later consider the share of total potential timber and biomass harvested, here we first consider the total potential volume. This is helps frame consideration of the sustainability and feasibility of the later harvest and biomass assumptions.

According to the USFS's forest inventory database (FIDO), there are a total of about 983,000 acres of forestland and timberland in Amador and Calaveras counties. These forested areas contain a total of 3.1 billion cubic feet of live tree volume with at least a DBH (diameter at breast height) of 5 inches. Therefore the average acre of forested land in the two counties holds about 16 MBF (thousand board feet).[2] The material that would not be used for merchantable timber could be converted to chips for use in a biomass facility. We vetted these potential timber and biomass volumes with local land managers to assess the realistic potential from the treatment areas. In practice, they reported that volumes accessible under current practices in the region associated with fuel treatment activities are substantially less than these per acre potentials. Vegetation composition, age, density, and accessibility all contribute to reducing the potential volume to actual harvestable volumes. Our volume estimates in following sections are based on actual harvest volumes observed by land managers available during fuel treatments in the project area. Actual volumes are typically much less than these calculations suggest as volume potential, suggesting that relatively small shares of the trees and biomass volume are part of the harvest assumptions.

7.4.2 Per unit revenue

In 2011, the average value of timber harvested from public and private forests in these two counties ranged from \$90–\$176 per MBF (California Board of Equalization 2011). A 2010 report from USFS states that existing biomass power plants in California typically pay \$25-\$45 per BDT for forest fuel (USFS 2010). These prices account for costs of transport and energy generation, as well as the revenue from the sale of the energy generated. We use these ranges of values to estimate the potential revenues derived from merchantable timber and biomass chips harvested during fuel treatments. These per unit values include existing subsidies. For example, the per BDT value for biomass represents the range in prices that biomass energy facilities typically pay for biomass in California. These businesses, however, often receive government subsidies to help bring revenues up enough to cover costs.

7.4.3 Potential harvest

BLM staff report that their maximum merchantable timber volumes have historically been 2-3 MBF/acre in the project area. USFS lands in the Mokelumne are generally considered to hold a

[2] There are about 5 board feet per cubic foot of timber volume for these timber stands.

higher harvest potential per acre. We apply 2 MBF to the BLM treatment areas with identified merchantable timber and compatible treatment techniques, and 3 MBF to the corresponding USFS lands.[3] Applying 2.5 MBF per acre of potentially harvestable timber to the general forest and steep slope areas as local land managers advised for non-federal areas, we estimate 152,000 MBF of total merchantable timber for those treatment areas with treatments compatible with timber removal.

For biomass volumes, we used the CAL FIRE database on existing forestry biomass (Geodatabase: BioVeg 2005; Methodology: Sethi 2005). The resulting average potential non-merchantable chip biomass in BDT per acre ranged from 4.5 to 5.3. Depending on the treatment type, some areas would yield both non-merchantable and merchantable timber, others would yield only non-merchantable timber, while other areas would not have any of its trees/biomass removed. Applied to the 95,946 acres of treatments from which biomass would be removed and 60,862 for which timber would be removed, the result in a total merchantable biomass removed of 464,000 BDT.

7.4.4 Total revenue of potential harvest

In order to calculate the total revenue associated with the modeled treatment scenario's harvests, we align the per unit revenues estimates with potential harvest volumes. With a per unit revenue of $90–$176 per MBF, the 152,000 board feet harvested during treatment could generate $14–$27 million in revenue. With a per unit revenue of $20–$45 per BDT, the 464,000 BDTs of merchantable biomass potentially collected during treatment could generate $12–$21 million in revenue. Due to access, market demand, and harvest capacity, it is unlikely that these full revenue potentials could be realized. Likewise, cultural and environmental sensitivity may require a reduction/relocation in the scope of treatments. Achieving these revenue levels would require carefully coordinated and staggered implementation over time.

7.5 Treatment Costs and Revenues over Time

In reality, the treatment scenario likely would play out over a multi-year period, as opposed to the single year of implementation that was required in the modeling scenario. To account for the potential effect of multi-year treatment implementation on the net present value (NPV) of treatment costs and revenues, we evenly distribute treatment costs and revenues over three time horizons: a 10-year treatment plan, a 20-year treatment plan, and a 30-year treatment plan. We also include a cost scenario involving maintenance every 5 years at a third of the initial cost for WUI areas and BLM-managed general forest, and at 20 years for all other land at 100% of the original treatment cost.[4] Table 7.4 summarizes these time horizons. For each scenario, we show the potential revenue from merchantable timber sales, the potential revenue from chip sales to biomass facilities, and the net treatment costs under four time horizons. All net present value calculations are based on a 3% discount rate.

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[3] Timber harvest volumes based on BLM and USFS staff recommendations.
[4] From personal communication with W. Haigh from the Bureau of Land Management, in October 2013.

Table 7.4: Summary of treatment costs and revenues over time[a] in $ millions

Treatment time horizon	*Treatment costs*	*Treatment costs with retreatment*	*Potential revenue from merchantable timber*	*Potential revenue from chips*	*Net cost (with retreatment)[b]*
1-year treatment plan	$46	$46	$14–$27	$12–$21	$34–($2)
10-year treatment plan	$39	$42	$12–$23	$10–$18	$32–$1
20-year treatment plan	$34	$47	$12–$23	$10–$18	$37–$6
30-year treatment plan	$30	$68	$9–$17	$8–$14	$60–$37

a: 3% discount rate. b: Net based on low end is lowest of the two revenue sources, and high end is based on sum of the high estimates for each revenue source. Values in parentheses represent net revenue (revenues greater than costs).

Net potential revenue faces the most uncertainty. For one, there is no available inventory data for merchantable timber at the AU-specific level. Likewise, the market demand and price for timber can fluctuate significantly over time. Biomass revenue potential is currently constrained by regional generation capacity and high transportation costs. The Buena Vista biomass power plant in Ione currently has 19 MW capacity, and the proposed Wilseyville site would likely have between 1-3 MW of capacity. The typical burn rate in biomass facilities is 1 BDT per MW per hour. This would equate to a regional demand for between 20 and 22 MW of approximate 175,000-193,000 BDT per year or more. Therefore, the regional biomass generation capacity is likely sufficient to meet the fuel generated by the 10-30 year treatment plans, assuming little competition from other forest biomass value-added utilization opportunities.[5]

7.6 Economic Impacts of Fuel Treatment

This section describes the economic activity potentially supported by treatment-related activities. First, we describe what we mean by economic activity, economic impacts, and economic impact analysis. Second, we provide a brief summary of the economic conditions in Amador and Calaveras counties, to help put our analysis in context. Finally, we describe and summarize the economic activity supported by treatment-related harvests, biomass collection, and prescribed burns.

7.6.1 What is Economic Impact Analysis?

So far, we have focused on the costs and revenues associated with fuel treatments. In this section, we focus on how those costs and revenues translated into economic impacts. The term *economic impacts* has a very specific definition to economists: the economic activity (e.g., the number of jobs, total income, and tax revenues) supported by a specific action. Because the implementation of fuel

[5] Assuming a 10 year time horizon, the 464,000 BDT would equate to 46,400 BDT/year, well within the range of demand annually from current capacity.

treatments requires labor, materials, and other goods and services, it supports economic activity. The tools economists use to estimate economic impacts provide gross, rather than net, results. In other words, these results do not necessarily reflect new jobs or new earnings. After all, resources used to fund fuel treatments could have been used to fund other projects. Similarly, some of the individuals employed by treatment-related spending could have worked on some other project, or may have left an existing occupation to pursue treatment-related work.

There are two types of economic impacts:

- *Direct impacts* describe the economic activity directly tied to spending associated with fuel treatments (e.g., wages paid to workers).
- *Secondary impacts* include indirect impacts and induced impacts. Indirect impacts occur as businesses buy materials from other businesses. They begin with changes in economic activity for businesses that supply the businesses implementing the treatments (e.g., the welding supply business that rents equipment is a secondary impact from rentals by construction contractors) and continue as those businesses purchase the goods and services they need to operate. Induced impacts represent the economic activity supported by changes in household incomes generated by direct and indirect impacts.

Each type of impact (direct and secondary) is described in terms of two variables that measure economic activity:

- *Output* is the broadest measure of economic activity and represents the value of production. Output includes intermediate goods plus the components of value added.
- *Employment* represents full-and part-time jobs. In some instances, this analysis refers to “job years”, which represents the equivalent of one full- or part-time job for one year. Ten job years, for example, could refer to one job for 10 years, five jobs for two years, 10 jobs for one year, etc.

7.6.2 Local Economic Context

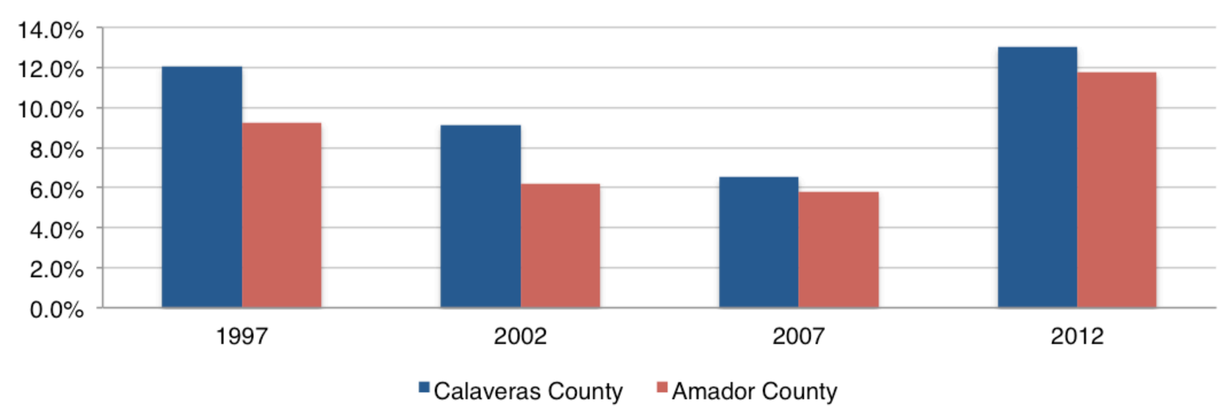
Economic impact analyses help economists understand the total economic activity an action can support. In order to understand local economic impacts, we must first look at the local economies in Calaveras and Amador counties. Table 7.5 summarizes demographic and employment data in the two counties. In 2012, the counties combined for an unemployment rate of about 12.4% with a total of 4,491 unemployed individuals. These unemployment rates remain high relative to historical unemployment rates and have grown sharply over the last 5 to 10 years. However, the most recent monthly unemployment data (December 2013) suggests that unemployment in these two counties has declined to 9.0% in Amador County and 9.4% in Calaveras County (Bureau of Labor Statistics 2014). The U.S. Census Bureau compiles data on the industry that employed individuals are currently working in, as well as their occupations, which is summarized in the top section of Table 7.6. The second row of this table is of particular importance to this analysis. A total of 357 individuals in Calaveras County and 279 in Amador County were employed in the agriculture, forestry, fishing and hunting, and mining industry category. The bottom section of Table 7.6 summarizes the number of employed individuals in the two counties, compared to the rest of the country, by occupation category. Across the two counties, about 7,200 individuals (about 23% of all employed individuals) were employed in two occupation categories: (1) natural resources, construction, and maintenance occupations, and (2) production, transportation, and material moving occupations.

The existing economic conditions in these two counties confirm that a number of individuals rely on jobs in the fields of natural resources, construction, maintenance, production, and/or transportation. Furthermore, an additional 21% and 25% of employed individuals in Calaveras and Amador counties, respectively, have service-related occupations that are primarily supported by other employed individuals living and doing business in the two counties. Together, these three occupation categories account for about half of the jobs currently held in Calaveras and Amador counties.

Table 7.5: Demographic and employment summary

	Calaveras County	*Amador County*	*Total*
Total population (2012 Estimate)	44,742	38,091	82,833
Persons below poverty level (2007-2011)	8.3%	10.0%	9.1%
Median household income	$55,256	$56,180	
Total labor force (2012 annual average)	19,430	16,673	36,103
Employed (2012 annual average)	16,899	14,713	31,612
Unemployed (2012 annual average)	2,531	1,960	4,491
Unemployment rate (2012 annual average)	13.0%	11.8%	12.4%

County-level unemployment rate (1997–2012)

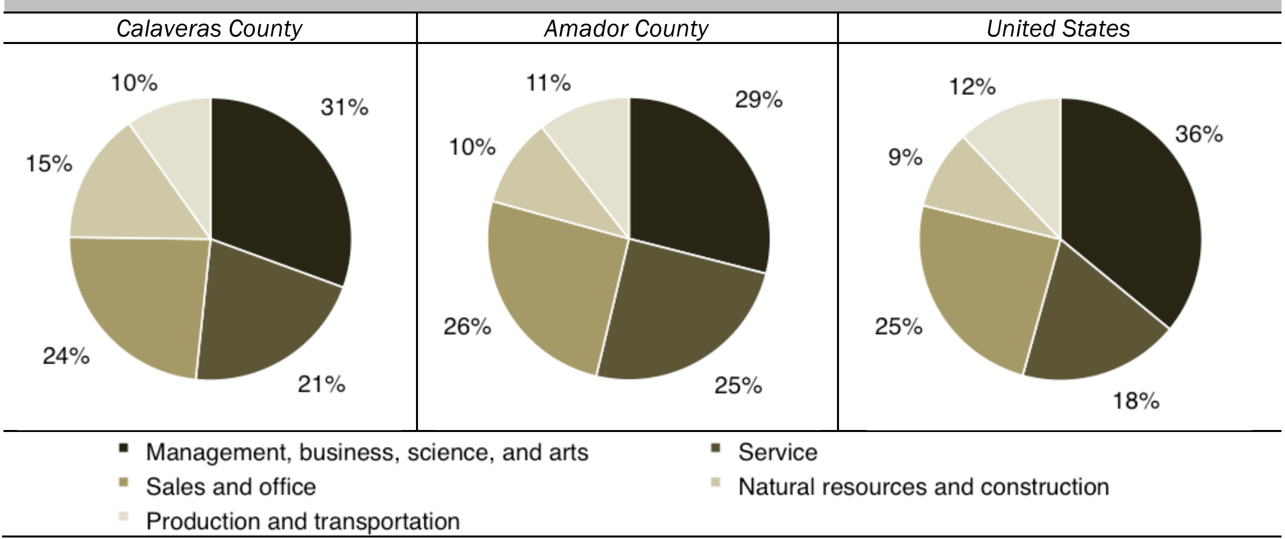


Source: U.S. Census Bureau. 2013. *State & County Quickfacts*. Retrieved on July 2, 2013; U.S. Bureau of Labor Statistics. 2013. *Local Area Unemployment Statistics*. Retrieved on July 2, 2013.

Table 7.6: Industry and occupation for employed individuals (2009-2011)

	Calaveras County	*Amador County*	*Total*
Civilian employed population 16 years and over	*17,962*	*13,202*	*31,164*
Agriculture, forestry, fishing and hunting, and mining	357	279	636
Construction	1,581	1,056	2,637
Manufacturing	781	752	1,533
Wholesale trade	523	170	693
Retail trade	2,262	1,878	4,140
Transportation and warehousing, and utilities	1,382	879	2,261
Information	489	135	624
Finance and insurance, and real estate and rental and leasing	579	422	1,001
Professional, scientific, and management, and administrative and waste management services	1,310	1,299	2,609
Educational services, and health care and social assistance	4,226	2,353	6,579
Arts, entertainment, and recreation, and accommodation and food services	1,474	1,970	3,444
Other services, except public administration	1,018	530	1,548
Public administration	1,980	1,479	3,459

Employed individuals, by occupation category (2009-2011)



Source: U.S. Census Bureau. 2013. *DP03: Selected Economic Characteristics, 2009-2011 American Community Survey 3-Year Estimates*. Retrieved on July 2, 2013.
Notes: Annual figures may differ slightly from other tables due to different data compilation methods by government agencies.

7.6.3 Treatment-related Harvests

The literature describing harvest-related economic impacts offers a range of job estimates that can be multiplied by harvest volume to estimate the number of direct jobs associated with harvest-related activities.[6] For this analysis, we use a range of job estimates identified in the literature: 8–11 jobs per million board feet (e.g., Conway 1994; Bormann 2006). For this analysis, however, we are primarily interested in examining the local impacts of harvest-related activities specific to Amador and Calaveras counties. To convert the job estimates from the literature to local estimates relevant to the study area, we make a number of assumptions:

- Conway (1994) found that about 51% of the direct jobs associated with harvest-related activities are in secondary wood manufacturing and paper production industries (Conway 1994). Many, if not all, of those jobs would occur outside the two counties. After removing those jobs from our assumptions, the range of direct jobs estimate decreases to about 4–5.5 direct jobs per million board feet.
- Lippke and Mason (2005) found that only about half of the total direct employment related to forestry in rural areas occurs near the harvest site. After removing these jobs from our assumptions, the range of direct jobs estimate decreases further to about 2-3 direct jobs per million board feet (Lippke 2005).

As described earlier, a total of about 152 million board feet of merchantable timber would be harvested from treatment-related activities. Applying our range of estimated direct jobs (2–3 direct jobs per million board feet) yields an economic impact of about 300 to 450 direct job-years within the two counties. The distribution of harvest over time determines how many of these job-years would occur sequentially, but under a 10-year treatment plan, this equates to 30-45 jobs. In 2011, Amador and Calaveras counties supported 85 jobs in the logging industry.[7]

These direct, harvest-related jobs likely will support additional economic activity in the region, such as secondary jobs. Secondary jobs include activities that rely on spending from the logging industry. For example, forest management jobs are largely captured as secondary impacts and are based on the purchases made by the logging industry. Secondary jobs also include activities that rely on spending from individuals working for the logging industry. According to IMPLAN 2011 data for Calaveras and Amador counties, the employment multiplier for the logging industry is 1.4; in other words, 10 direct jobs in the logging industry support an additional 4 jobs throughout the economy. Applying this multiplier to the 30-45 direct jobs calculated earlier yields 12–18 local secondary jobs, or 42-63 total jobs supported.

The direct timber output of treatment-related harvests is the total estimated revenue from the activities ($14–$27 million), as described earlier in this section. The secondary output represents the logging industry's purchases from suppliers for goods and services, such as equipment and tools. It also includes those suppliers' purchases and employee spending. For Calaveras and

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[6] Jobs are measured in terms of full‐year‐equivalents (FYE). One FYE job equals work over twelve months in a given industry (this is the same definition used by the federal government's Bureau of Labor Statistics). For example, two jobs that last six months each in 2012 count as one FYE job in 2012. A job can be full‐time or part‐time, seasonal or permanent; input-output analysis counts jobs based on the duration of employment, not the number of hours a week worked. In other words, one job is twelve monthly paychecks. It may be a mix of several individuals holding a one position at a time throughout one year, and this would equal one FYE job, according to Labor Department statistics.

[7] IMPLAN 2011 data, Calaveras and Amador counties. IMPLAN provides input-output modeling of economic sectors and their interdependencies to estimate additional jobs and income generated by direct demands.

Amador counties, the output multiplier is 1.85. In other words, for every million dollars the logging industry spends, another $850,000 is spent elsewhere in the economy. The secondary impacts total $12–$23 million in output in the local economy, resulting in a total output of between $26 and $50 million.

Other studies have found higher employment numbers per board feet of timber, and per dollar of treatment expenditures (UMass 2009).[8] Such studies suggest that with intentional efforts to generate local labor demand with treatment and biomass activities, particularly among unemployed groups, the total impact on job creation could likely be significantly higher.

7.6.4 Biomass Chips

Collecting and supplying chips to biomass facilities for energy production supports additional employment. As with timber harvest-related jobs, the literature provides a range of direct job estimates for biomass collection efforts: about 300–400 direct jobs per million BDTs (the treatments would yield approximately 464,000 BDTs) (OFRI 2006). Based on the stated objective of biomass activities in the region to rely upon local labor, we assume all of these jobs could be sourced from local county labor forces.[9] Applying our range of direct jobs estimate (300–400 direct jobs per million BDTs of chips) to an approximated 0.5 million BDTs collected during treatment yields a total of 150–200 direct jobs. Furthermore, after applying a secondary jobs multiplier of 2.0, these direct jobs would help support an additional 150–200 secondary jobs within the two counties.

The direct output of biomass collection during treatment represents the total estimated revenue from the activities ($12–$23 million) as described earlier in this section. According to the 2011 IMPLAN data, the output multiplier for collection and gathering of forest products is 1.4, which leads to a total secondary impact of $5–$9 million in output for other industries in the local economy. Similar to the secondary output for logging industries, these impacts represent supply-chain purchases needed to collect and supply chips to biomass facilities, as well as employee spending in the local region.

7.6.5 Prescribed Burns

The literature describing the economic impacts of prescribed burns offers a range of direct job estimates: 2–9 direct jobs per 1,000 acres of burn area (Crone 2001, Kim 2010). As with our analysis of biomass-related jobs, we assume that the Amador Calaveras Consensus Group stated objective to source these jobs from the local county labor force would be successful.[10] Applying our range of direct jobs estimate to the 4,000 acres receiving burn-related treatment, a total of 8–36 direct jobs within the two counties would be supported. Furthermore, after applying a secondary

[8] E.g., for every $1 million invested in biomass, it can create a total of 17.36 jobs (direct, indirect, and induced jobs) and for every $1 million in forest treatment work, the total induced jobs is 39.7.

[9] If these efforts to fully utilize local labor are unsuccessful, an assumption similar to for timber harvest would be appropriate - that half the jobs would be locally sourced.

[10] As with biomass-related jobs, if these efforts to fully utilize local labor are unsuccessful, an assumption similar to for timber harvest would be appropriate, that half the jobs can be locally sourced.

jobs multiplier of 2.0, these direct jobs would help support an additional 8–36 secondary jobs within the two counties.

The direct output of prescribed burns during treatment represents the total cost of the activities ($7–$20 million) as described earlier in this section. According to IMPLAN, the output multiplier for support activities for agriculture and forestry is 1.45, which leads to a total secondary impact of $0.6 - $0.7 million.

7.6.6 Costs of Fuel Treatments

Overall, there are two schools of thought with regards to forest management related to wildfires: (1) preventative fuel treatments and (2) reactive wildfire suppression. Because fuel treatments do not prevent fires, but reduce the risk and intensity of fires, both the preventative and reactive approaches will require some degree of postfire restoration, although the costs associated with restoration post fire in previously treated areas can be significantly less than the costs associated with fires that burn untreated areas (Chapter 4). Focusing on fuel treatments, there are three methods that are predominately used to reduce the risk of forest fires: (1) biological methods (e.g., prescribed fires and grazing), (2) chemical methods (e.g., herbicides), and (3) mechanical methods (e.g., forest thinning).

There are several challenges in estimating average fuel treatment costs. As described by Reinhardt, et al., there is a "paucity of consistent reporting data maintained by federal wildland agencies and the unique physical and managerial characteristics of fuel treatments have limited thorough assessments of the cost of individual fuel treatment. Additionally, data issues are complicated by the fact that agencies may conduct fuel treatments through timber sales, stewardship contracts, or traditional hazardous fuels funding" (Reinhardt 2008). The literature shows that several variables contribute to average treatment costs. Some of the most influential variables include:

- Size of treatment area
- Proximity to WUI
- Proximity to threatened/endangered species habitat
- Slope
- Biomass-related activity
- Treatment type (prescribed burn vs. harvest)
- Ability to offset costs with revenue from harvested materials

In the following sections, we will describe at greater detail two of treatment methods that are primarily employed in the modeled treatment scenario used in this analysis: prescribed burning and mechanical treatments.

7.7 Prescribed Burns

While there are several different types of biological methods for conducting fuel treatments, the most common are prescribed fires and grazing. According to the USFS's fuel treatment actions of 1998 and 1999 (describing actions that mostly occurred in the South), the average cost of implementing prescribed fire was $55 and $70 per acre (respectively, in 2012 dollars). Costs varied across regions from a low of $20 per acre in Region 8 (Southern) to $578 per acre in Region 10 (Alaska). Per acre costs ranged from $71 to $108 in Region 2 (Rocky Mountain), Region 4 (Intermountain), Region 6 (Pacific Northwest), and Region 9 (Eastern) (in 2012 dollars). Per acre costs were $129 in Region 1 (Northern) and $197 in Region 5 (Pacific Southwest) (in 2012 dollars) (Kline 2004).

From 1985 to 1994, average costs per acre for different methods of prescribed burning in national forests were: $261 for slash reduction burning, $121 for management-ignited prescribed fire, $162 for managing natural fires, and $90 for brush, range, and grassland prescribed fires (2012 dollars). Treatment scale (area of treatment) and labor costs tend to be the most influential cost factors (Kline 2004). Hartsough et al. (2008) compiled per acre costs (based on expert estimates) for small, medium, and large prescribed fires in five locations in the western U.S. (see Table 7.7). For this analysis, we use the site-specific cost of $324–$390 per acre from the Central Sierra Nevada Range in California.

Table 7.7: Expert estimates of costs (per acre) for prescribed burns (2012$)

Location	*Burn treatment*	*Large burn*	*Medium burn*	*Small burn*
Northeastern Cascades, WA	Spring under burn using a strip head fire	$288	$1,055	$1,151
Northern Rocky Mts., MT	Fall under burn	$144	$475	$2,254
Blue Mountains, OR	Fall under burn	$34	$72	$158
Central Sierra Nevada, CA	Fall under burn using a combination of backing and strip head fires	$324	$355	$390
Southern Sierra Nevada, CA	Fall and spring under burn (3 times each)	$168	$249	$422

Source: Hartsough, R., S. Abrams, R. Barbour, et al. 2008. “The Economics of Alternative Fuel Reduction Treatments in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study.” *Forest Policy and Economics*. 10:344-354.

7.8 Mechanical Treatments

Mechanical fuel treatments often include the harvesting of materials from the forest. These materials can be burned on site (e.g., pile burned) or removed from the forest and sold. This section focuses on the costs and benefits of past efforts to use mechanical treatments to reduce future fire risk.

One benefit that distinguishes mechanical treatments from other treatment types is the revenue generated from timber harvests. Skog points out the importance of separating and marketing large-diameter logs for higher value products (Skog 2006). Table 7.8 shows the average per acre treatment costs for mechanical fuel treatments under a number of different treatment scenarios based on the slope of the site. In general, treatment costs increase as the slope of the treated area increases beyond a certain threshold. All the options in the table have the representative costs associated with forest thinning efforts that remove 25%-50% of the biomass from the forested area.

For this analysis, we identified the most relevant option from this study and augmented the costs with evidence from other studies that show specific characteristics on cost that relate to facets of our analysis. For example, Calkin found that treatment near the wildland-urban interface (WUI) increases the cost of that treatment by approximately 62%. For all treatment efforts in the WUI, or near other forms of development, we inflated the average cost per acre by 62% to reflect this potential cost difference. Calkin also found that biomass removal associated with harvest-related treatment strategies can more than double the costs of fuel treatments (Calkin 2006). For this analysis, we assume that the cost estimates from Skog have already incorporated the costs of biomass collection efforts (Skog 2006).

Table 7.8: Estimated treatment cost (2012$/acre)

Treatment	*Average treatment cost*	
	Slope <40%	*Slope >40%*
1A	$1,036	$2,035
2A	$968	$2,101
3A	$980	$2,256
4A	$794	$2,078
1B	$1,131	$2,110
2B	$1,012	$2,139
3B	$1,035	$2,266
4B	$1,092	$2,091

Source: Skog, K. and R. Barbour. 2006. Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the U.S. West. U.S. Forest Service Proceedings RMRS-P-41.

7.9 Treatment Cost Literature Review

In the previous two sections, we outlined some of the literature that describes costs associated with various forms of fuel treatments. In order to most accurately estimate costs associated with our specific treatment scenario, we aligned the different types of treatment in our scenario with different components of treatment costs as they are listed in the literature. Table 7.9 shows all the treatment codes for the treatment scenario, our estimated range of per acre treatment costs, a short description of our assumptions, and the relevant sources.

As previously stated, these costs depend on a number of factors, including the cost of labor and transportation, as well as the physical characteristics of the forests and the topography of the area. Additionally, if the scenario we describe extends into longer implementation periods, costs can significantly increase as administrative efforts span over more and more years.

Table 7.9: Treatment cost literature review summary

Land type	*Treatment code*	*Treatment cost ($/acre)*	*Description of assumptions*	*Sources*
CSOPACs	111	$324–$390	(1) Central Sierra (Under burn using backing and strip head fires). (2) Blodgett Experimental Forest (Eldorado/Stanislaus/Tahoe National Forests) Sierra Mixed Conifer. (3) Based on expert opinion.	Hartsough, B. et al. 2008. "The Economics of Alternative Fuel Reduction Treatment in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study." *Forest Policy and Economics*. 10:344-354.
General forest	322	$749–$1,123	(1) Range depends on specific treatment scenario. (2) Treatment scenarios assume 25%-50% removal. (3) Treatment scenarios both even-aged and uneven-aged forests. (4) Assumes <40% slope	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41.
Key roads	323	$1,213–$1,819	(1) Same as General Forest 322, but inflated by 62% to reflect added cost of treatment in WUI.	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41. Calkin, D. and K. Gebert. 2006. “Modeling Fuel Treatment Costs on Forest Service Lands in the Western United States.” *Western Journal of Applied Forestry*. 21(4):217-221.
Parcels with structures	323	$1,213–$1,819	(1) Same as General Forest 322, but inflated by 62% to reflect added cost of treatment in WUI.	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41. Calkin, D. and K. Gebert. 2006. “Modeling Fuel Treatment Costs on Forest Service Lands in the Western United States.” *Western Journal of Applied Forestry*. 21(4):217-221.
Riparian	311	$749–$936	(1) Same as General Forest 322, but including only the lower half of the range due to decreased volume removed.	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41.
Steeply sloped	322	$2,020–$2,249	(1) Range depends on specific treatment scenario. (2) Treatment scenarios assume 25%-50% removal. (3) Treatment scenarios both even-aged and uneven-aged forests. (4) Assumes >40% slope.	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41.
Transmission lines	323	$1,213–$1,819	(1) Same as General Forest 322, but inflated by 62% to reflect added cost of treatment in WUI.	Skog, K., and R. Barbour. 2006. “Estimating Woody Biomass Supply from Thinning Treatments to Reduce Fire Hazard in the US West.” USFS Proceedings RMRS-P-41. Calkin, D. and K. Gebert. 2006. “Modeling Fuel Treatment Costs on Forest Service Lands in the Western United States.” *Western Journal of Applied Forestry*. 21(4):217-221.
Wilderness-roadless	111	$324–$390	(1) Central Sierra (Under burn using backing and strip head fires). (2) Blodgett Experimental Forest (Eldorado/Stanislaus/Tahoe National Forests) Sierra Mixed Conifer. (3) Based on expert opinion.	Hartsough, B. et al. 2008. "The Economics of Alternative Fuel Reduction Treatment in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study." *Forest Policy and Economics*.10:344-54.

Notes: CSOPAC = California spotted owl protected activity centers.
These numbers are based on our initial literature review but the treatment costs used in the chapter are based on local estimates, located in Table 7.3.

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Chapter 8: Carbon Analysis

Forests can act as carbon sinks, as well as carbon sources. Through appropriate forest management practices, the forest sector can increase its carbon stocks and help reduce greenhouse gas (GHG) emissions, helping the state meet its long-term goals to address climate change. A particular area worthy of further consideration is the issue of high-severity wildfire and how management may reduce the associated risk of significant emissions and increase forest resilience in a warming climate.

This section seeks to assess the potential climate benefits of fuel treatments chosen for the Mokelumne watershed. Specifically, it explores whether such treatments would decrease the amount of carbon released under the modeled Five Fires scenario, by how much, and what the economic value of these avoided emissions might be. To help answer this question we (1) assess the total amount of carbon in the watershed, (2) assess the amount of carbon removed via treatments, (3) assess the emissions released during wildfires for both the treated and untreated scenarios, and (4) estimate the value of these avoided emissions. While the information in this section could inform efforts to address fire as part of climate policy in California, it is not intended to suggest specific criteria for how GHG reductions should be measured.

8.1 Carbon in the Watershed

We assessed carbon in the Mokelumne watershed using a 2005 California Department of Forestry and Fire Protection (CAL FIRE) GIS database and report called "Biomass Potentials from California's Forests and Shrublands" (Sethi 2005). CAL FIRE uses FIA (Forest Inventory and Analysis) data stratified to CWHR (California Wildlife Habitat Relationships) habitat types and then converted to an average live tree and shrub biomass (in bone-dry metric tonnes) per hectare. CAL FIRE uses this FIA data as part of its statutory requirements under AB 32 and the US Forest Service (USFS) is also a party in this effort. The biomass weight is converted to carbon using 0.5 as the conversion factor (Penman et al. 2003).

The numbers in the CAL FIRE database do not include litter, duff, dead trees, surface fuels, or soil carbon – which collectively can compose 25-45% of the entire forest carbon pool and a significant component of carbon emissions during fires (Campbell et al. 2007; North et al. 2009). As a result we assess the additional carbon from these pools using the USFS Fuels Characteristic Classification System (FCCS) (Ottmar et al. 2007). We assign an FCCS-specified amount of woody fuels, duff, and litter based on the CWHR codes assigned to each pixel. The cross-walk is based on the dominant vegetation type for each pixel, and where applicable, the size-class of trees present. Unfortunately, the FCCS vegetation types are at a broader classification than the CWHR vegetation types, so we could not find a fuel characterization for each CWHR type, and some grouping was required. Due to limits in the vegetation data set, including its large pixel size, the survey methods for the original data set, the age of the data (some are close to 10 years old), and the use of a cross-walk with potential errors in validation, caution should be used when considering this analysis for fine-scale planning.

8.2 Results – Carbon in the Watershed

Carbon in the watershed is highly variable due to an elevational gradient that encompasses vegetation zones from grasslands to alpine tundra. Results include carbon from live trees, woody fuels, litter, and duff. The analysis shows that the greatest amount of carbon is in the highly productive mixed-conifer belt ranging from 3,000 to 6,000 feet in elevation, where above-ground carbon can be as high as 260 tonnes per hectare (a tonne is a metric ton, equal to approximately 2,205 pounds; 1 hectare equals approximately 2.5 acres). Even in this belt, though, the amount of carbon is variable depending on site characteristics such as vegetation type and disturbance history (including whether the site has been recently logged or had a fire).

Table 8.1 shows the results of the carbon analysis in the watershed. The much lower average carbon in the Pardee watershed is likely due to the fact that that its area is generally at a lower elevation and has lower tree biomass per acre, with more acres in chaparral and oak woodland, than the mid-elevation Tiger Creek Afterbay watershed, which has more acres with conifer forests.

Table 8.1: Estimates of above-ground carbon in the Mokelumne watershed (tonnes)

	Hectares (ha)	*Total carbon (tonnes)*	*Average carbon (tonnes/ha)*
Pardee watershed	56,976	3,955,849	69
TCAB watershed	38,983	4,517,202	116
All upper Mokelumne	149,805	14,887,693	99

8.3 Carbon Removed by Treatment

Table 8.2 shows the total and average carbon per acre within the treated analysis units (TAU). We show pretreatment and posttreatment amounts for the portions of the Mokelumne watershed that drain to both Tiger Creek Afterbay and Pardee Reservoir based on the biomass volume estimated to be removed during treatments. Within the TAUs, fuel treatments remove a portion of the carbon as either chips or sawlogs. The CAL FIRE biomass database and accompanying report provide estimates of biomass removed based on a rule set that describes a typical fuel treatments operation that would remove small diameter trees, resulting in removal of 4-17% of the above-ground tree biomass at a site (Sethi 2005).

We estimate the amount of biomass removed based on the treatment prescriptions described in Chapter 7 of this report and the estimates from the CAL FIRE database. Errors in the estimate of material removed could occur due to differences in treatment type between the CAL FIRE database and the modeled treatment for this study. For example, mastication leaves a portion of the biomass on-site as shredded organic material strewn over the ground. Prescribed fires can also remove a portion of the carbon through a low-intensity fire that combusts fine fuels, litter, and duff, and kills vegetation that will then decompose and emit carbon over time. The CAL FIRE database simply assumes that the treatments removed material from the site by mechanical means and therefore we could not model the carbon impact of mastication or prescribed fire.

Additionally, we did not assess the fate of the material removed, which could be used to create energy or to wood products. For simplicity, we assume that once biomass is removed it is no longer part of the carbon assessment. Using the material for energy creation could offset the carbon released by other energy sources, and thus alter the total carbon impact of fuel treatments (Winford and Gaither 2012). If the material is used for wood products, it can remain in use for 30 or more years, depending on the type of product (Earles et al. 2012). We identify this as a gap and hope that future analysis can resolve this question. We do not assume a timeframe for these treatments to occur, but present it as the total potential biomass estimated removed by the treatments. In reality, treatments will likely occur over several years to decades. Table 8.2 shows carbon in the TAUs within the Pardee Reservoir and the Tiger Creek Afterbay watershed, before and after fuel treatments.

Table 8.2: Estimate of carbon stocks pre and post thinning (in tonnes)

	Pardee Reservoir Watershed	*Tiger Creek Afterbay Watershed*
Treated ha	27,988	10,995
Carbon, pre-treatment	1,582,670	1,449,725
Average carbon, pre-treatment	56.55	131.85
Carbon post-treatment	1,032,028	1,179,471
Average carbon, post-treatment	36.87	107.27
Carbon removed	550,643	270,254
Average carbon removed per ha	19.67	24.58

8.4 Carbon Emissions from Fires

During a fire, the combustion of foliage, bark, live wood, dead wood, duff, and soil litter emit carbon to the atmosphere. The amount of carbon emitted depends on the severity of the fire and the type of material. Direct emissions from wildfires vary by fire severity, with high-severity fires combusting more biomass and creating more emissions (Campbell et al. 2007). Duff and litter are often completely combusted and account for the majority (57%) of carbon emissions during a fire (Campbell et al. 2007). Carbon emissions from live trees, dead trees, and foliage make up the rest of the carbon emissions, but these components are often not completely consumed by fire; some will survive while others will die from damage sustained during the fire and slowly decompose. Research in the Sierra Nevada has shown that an untreated forest with a high-severity fire suffered 97% tree mortality, while a treated forest had 53% mortality (North and Hurteau 2011). The process of decay is slow, and it may take up to 30 years for these dead trees to decompose and emit the carbon they contain (Harmon 2001).

For this analysis we estimate the amount of biomass burnt by a fire by assuming that the fraction of the biomass that is immediately combusted will vary by fire severity and fuel type. We use combustion fractions for live trees, surface fuels, litter, and duff – which vary by fire severity –

from Campbell et al. (2007) for low combustion-fraction estimates. For higher estimates, we use the 0.30 combustion fraction of woodlands and forests along with the 0.90 combustion fraction for herbaceous material – which do not vary by fire severity – as reported in Wiedinmyer et al. (2006). These two combustion fractions represent a potential range for the combustion of biomass during fires – the actual percentage of vegetation combusted during a fire will depend upon the weather, fuels, and topography within the fire. None of the combustion factors used for this study came from a Sierra Nevada-specific study, although such studies are forthcoming. Recent fires in the region, including the 2013 Rim Fire, had higher fire severities than that reported by Campbell et al. (2007) and, given the expected temperature increases with climate change, we expect to see increased fire severities that could increase the combustion factors associated with fires. Fire severity in our modeled fires is based on modeled flame lengths, as described in Appendix A. We make estimates of tree mortality following a wildfire based on the fire severity and the rates reported by North and Hurteau (2011), but we do not add these estimates to this analysis due to uncertainty of the time frame of decomposition.

The probabilities of the modeled fires and the selected fire perimeters are discussed more in Chapter 3 and Appendix A. For this analysis, we simply assume that a fire occurs within the lifespan of the treatment – typically 10-20 years for mixed-conifer forests, depending on treatment type, treatment intensity, topography, and site productivity (Stephens et al. 2012; Chino et al. 2012; Collins et al. 2013). Refer to Chapter 6.5 for specific probabilities of these fires and the likelihood that a fire does happen in the project timeframe.

Estimates of carbon emissions shown in Table 8.3 are for pretreatment conditions. We combine surface fuels, litter, and duff into one category for ease of reading. Fire A is within the Tiger Creek Afterbay watershed and Fires B through E are in the Pardee Reservoir watershed. The carbon emissions using the combustion factors from Campbell et al. (2007) (denoted as C*) range from 17-30% of the total carbon on site pre fire, while those from Wiedinmyer et al. (2006) range from 29-49% of total carbon on site pre fire. Potential carbon emissions from tree decay show the estimated emissions from decay over the expected 30-year decay period for mixed-conifer species (Harmon et al. 2001). While we report this result, we do not add it to resulting calculations, given uncertainty in the magnitude and timing of emissions from decay.

Table 8.4 describes the carbon emissions from fires A-E after treatment. Table 8.5 compares the emissions from the low and high estimates pre and post treatment. Fuel treatments that alter the size and intensity of wildfires reduce the amount of carbon emitted by fires from 36-85%, depending on the fire. The fuel treatments also reduce the expected emissions from decaying trees, because of the modeled reduction in fire severity and fire size.

Table 8.3: Analysis of carbon emissions from fires – pretreatment

	Hectares - pre treatment	*% at high severity*	*Tree carbon*	*Ground fuels carbon*	*C emissions-Campbell*	*C emissions-Wiedinmyer*	*Potential C emissions from tree decay*
Fire A	7,712	22	628,598	300,134	277,905	458,700	120,339
Fire B	7,618	39	446,721	198,801	196,919	312,937	156,761
Fire C	2,242	16	91,958	26,220	25,909	51,185	13,502
Fire D	1,758	18	36,986	7,565	8,106	17,904	6,061
Fire E	1,224	26	35,533	6,597	7,457	16,597	8,246

Table 8.4: Analysis of carbon emissions from fires – posttreatment

	Hectares - post treatment	*% at high severity*	*Tree carbon*	*Ground fuels carbon*	*C emissions-Campbell*	*C Emissions-Wiedinmyer*	*Potential C emissions from tree decay*
Fire A	5,395	6	316,433	209,641	177,930	283,607	17,725
Fire B	4,778	19	181,633	122,827	108,679	165,034	31,217
Fire C	545	1	10,487	4,913	4,246	7,567	76
Fire D	1,006	9	7,624	3,342	2,997	5,295	598
Fire E	453	17	5,338	2,511	2,295	3,861	815

Table 8.5: Reduction in carbon emissions from fuel treatments

	*Reduction in emissions – C**	*Reduction in emissions – W**	*Mid-point between the two estimates*
Fire A	99,974	175,094	140,000
Fire B	88,240	147,903	120,000
Fire C	21,663	43,618	33,000
Fire D	5,110	12,609	8,900
Fire E	5,161	12,736	8,900

Note: C* denotes the use of combustion fractions from Campbell et al. (2007); W* uses combustion fractions from Wiedinmyer et al. (2006). Calculated by subtracting the "C emissions" columns in Table 8.4 from the corresponding columns in Table 8.3.

Table 8.6: Carbon impact of fuel treatments compared with emissions from fires

	Carbon removed by treatment	*Total carbon removal - C**	*Pre-treatment – fire emissions - C**	*Carbon impact - C**	*Total carbon removal - W**	*Pre-treatment – fire emissions - W**	*Carbon impact - W**
Fire A	115,517	293,447	277,905	(15,542)	399,123	458,700	59,577
Fire B	105,309	213,988	196,919	(17,069)	270,343	312,937	42,594
Fire C	12,116	16,362	25,909	9,547	19,684	51,185	31,501
Fire D	10,415	13,411	8,106	(5,305)	15,710	17,904	2,195
Fire E	5,374	7,670	7,457	(213)	9,235	16,597	7,362

Note: *C removed by treatment* = carbon removed by fuel treatment. *Total carbon removal* = carbon removed by treatment plus the carbon emissions from the fire (post treatment). *Carbon impact* = the carbon released by a wildfire pre treatment minus the carbon removed by treatments and posttreatment wildfire emissions. Negative values are shown in parentheses and red text and indicate where treatments did not have a net carbon benefit post fire.

To answer the question of whether fuel treatments had a net positive carbon impact, we also need to consider the carbon impact of removing biomass during fuel treatments. Table 8.6 shows the total carbon impact of fuel treatments compared to the pretreatment scenario. In this table we added the carbon removed by fuel treatments ("C removed by treatment") to the carbon emissions post treatment and compare it to the carbon emitted by fire from the pretreatment fires. We use "Total carbon removed" to show the carbon removed by treatment and the estimated carbon emissions from wildfires (post treatment) for each fire. Because we have two different estimates of emissions, we use "– C*" to denote estimates of emissions based on Campbell et al. (2007)'s equations and "– W*" to denote estimates of emissions based on Wiedinmyer et al. (2006)'s equations. We then compare this amount to the carbon released by a wildfire prior to treatment ("Carbon impact" in the table).

This shows the impact of using various combustion factors on the question of whether fuel treatments have a net positive or negative carbon impact. For the modeled fires, the lower combustion factors (from Campbell et al. 2007) generally do not show a net carbon benefit from fuel treatments, but the high combustion factors (from Wiedinmyer et al. 2006) do. Where the carbon impact value is positive, estimates of the carbon left on site post treatment and post fire in trees that will continue to grow and sequester more carbon is greater than no-treatment postfire estimates. Because of the uncertainty of the combustion factors for a hypothetical fire in the Mokelumne watershed, we will use the midpoint of these emissions in the next section, which estimates the economical benefits to society.

8.5 Value of Avoided Carbon Emissions

Economists use the social cost of carbon to estimate the value of changes in greenhouse gas emissions. The social cost of carbon represents "the full global cost today of emitting an incremental unit of carbon at some point of time in the future, and it includes the sum of the global cost of the damage it imposes on the entire time it is in the atmosphere" (Shaw 2009). There are currently over 200 different estimates of the social cost of carbon. One review of the literature found values ranging from about $7 to over $100 per tonne of CO_2e (CO_2 equivalent) (Shaw 2009).

Over the past decade, several voluntary and regulatory carbon markets have emerged around the world along with several attempts at taxing carbon. Table 8.7 summarizes the total volume, total value, and per unit value of carbon traded in voluntary and regulatory carbon markets around the world in 2011. The average carbon price across these markets was about $21 per tonne of CO_2e. In addition to these carbon markets, many public agencies around the world have proposed or implemented carbon tax schemes (e.g., South Africa, India, Japan, South Korea, Australia, New Zealand, Denmark, Finland, and France). In 2008, British Columbia passed the Carbon Tax Act, which consumers pay when they purchase fossil fuels in the Province. The carbon tax rate has creased each year and in July 2012 it was set at $27 per tonne of CO_2e (Ministry of Finance 2013).[1]

Table 8.7: Voluntary and regulatory carbon markets (2011 summary)

Carbon Market	*Tonnes of CO_2e (millions)*	*Total market value (millions)*	*Average value per tonne ($/tonne of CO_2e)*
Voluntary carbon markets	78	$576	$7.38
European union emission trading scheme	6,463	$147,848	$22.88
Primary clean development mechanism	239	$3,320	$13.86
Secondary clean development mechanism	1,500	$23,250	$15.50
Kyoto protocol	39	$318	$8.15
Regional greenhouse gas initiative	99	$249	$2.52
Annex 1 market (Kyoto protocol)	4	$12	$3.31
New Zealand carbon market	22	$351	$16.12
California carbon allowance	4	$63	$17.36
Others	22	$40	$1.84
Total	*8,468*	*$176,027*	*$20.79*

Source: Ecosystem Marketplace. 2012. *Developing Dimension: State of the Voluntary Carbon Markets 2012*. May 31.

A recent publication from the U.S. Interagency Working Group on Social Cost of Carbon recommends using even higher values than those described above (U.S. Interagency 2013). The group's estimate is based on the value of potential damages associated with incremental increases in carbon emissions, including agricultural productivity, human health, property damages, and ecosystem services. The group's estimates range from about $13 to $64 (in 2012 dollars) per tonne of CO_2 in 2013, depending on the discount rate (5.0%-2.5%). The group also suggests that at the high end of the 95% confidence interval, the social cost of carbon could be as high as about $110 per tonne of CO_2 in 2013.

To account for carbon values in existing markets, particularly California, government taxes, and the Interagency Working Group on Social Cost of Carbon estimates, in Table 8.8 we consider a range of $17 (Total Market Value) to $63 (Total Social Value) per tonne of CO_2e.

The difference in carbon emissions from the fires with and without fuel treatments totals $5 million to $19 million for the five fires. The effect of treatments on the difference in emissions pre and post fire for the Tiger Creek Afterbay and Pardee Reservoir watersheds is worth $14 million to $52 million dollars (Table 8.8). The specific timing of the avoided emissions, in terms of when the fires would occur, would determine the present value, as more distant future avoided emissions are less valuable. For example, if these avoided emissions did not occur for 20 years, the carbon value at a 3% discount rate would be between $3 million and $11 million. While there are good reasons to use low discount rates when considering benefits and costs of carbon mitigation and adaptation

[1] $30 Canadian at exchange rate of 1.1 Canadian to U.S. British Columbia.

(e.g., Weitzman 2007), the presence of current opportunities to mitigate carbon emissions does dictate that society would likely be better off with current mitigation rather than delayed mitigation.

Table 8.8: Value of avoided carbon emissions

Carbon source	*Tonnes of CO_2e*	*Total market value ($17/tonne)*	*Total social value ($63/tonne)*
Tiger Creek Afterbay Watershed pre- and post-T difference	550,000	$9,400,000	$35,000,000
Pardee Reservoir Watershed pre- and post-T difference	270,000	$4,600,000	$17,000,000
Treatment total	*820,000*	*$14,000,000*	*$52,000,000*
Fire A	140,000	$2,300,000	$8,700,000
Fire B	120,000	$2,000,000	$7,400,000
Fire C	33,000	$550,000	$2,100,000
Fire D	8,900	$150,000	$560,000
Fire E	8,900	$150,000	$560,000
Fire emissions total	*310,000*	*$5,200,000*	*$19,000,000*
Treatment and emissions total	*1,100,000*	*$19,000,000*	*$71,000,000*

Note: Fire-specific estimates are based on the midpoint column in Table 8.5 above.

8.6 Discussion of Results

This analysis shows that fuel treatments reduce carbon emissions from the modeled fires by 38-77%. These avoided carbon emissions are almost entirely due to the smaller size and lower severity levels of the fires post-treatment. As shown in Table 8.6, using the higher combustion factors from Wiedinmyer et al. (2006), avoided carbon emissions from fires in the untreated areas are greater than the carbon that fuel treatments remove plus emissions from a fire. This suggests that fuel treatments can actually help increase carbon stocks by reducing the size and severity of fires (Hurteau and North 2009). Using the lower combustion fractions from Campbell et al. (2007), only Fire C has more avoided carbon emissions from fires in untreated areas than the carbon removed by fuel treatments plus fire emissions in the treated areas. This could be explained because Fire C had a 95% reduction in modeled fire severity. All other modeled fires using the Campbell et al. (2007) combustion factors have less avoided emissions from wildfires in the untreated areas than the treated areas. This would suggest that fire severity, and the resulting combustion factors, has a determining role in whether fuel treatments help increase carbon stocks in the forest given a wildfire or not.

From an economic perspective, the value of the carbon volumes at stake is potentially in the millions to tens of millions of dollars. If biomass removed in treatment can be sequestered or offset other emissions (e.g., bioenergy facility offsetting coal power emissions), the additional value can likely reach into the millions. We realize that, in practice, fuel treatments will not likely cover as many acres as in our simulation treatment scenario and therefore the actual volumes would likely be less, as would the costs. For reduced emissions due to smaller fires attributable to treatment, the value of carbon that remains sequestered also reaches into the millions of dollars.

Overall, carbon volumes and avoided emissions for our scenarios are likely in the tens of millions of dollars in overall social value, and would be in the millions for market opportunities in California, if such market participation is allowed. Regardless, market rates demonstrate the cost to Californians to achieve these equivalent avoided emissions as the least costly option.

An important point to note is that this analysis only looks at the impact of one fire and one treatment upon any particular pixel over the 30-year planning period. Whether any particular fuel treatment provides for greater carbon stocks post fire depends on the fire return interval (FRI), or the number of fires that occur in the area in a given span of time, and the type of treatment (Winford and Gaither 2012). If the vegetation type experiences frequent fires, such as the 11-year mean FRI of ponderosa pine (van de Water and Safford 2011), then fuel treatments may provide for greater carbon stocks post fire. However, vegetation in longer fire-return intervals, such as the 40-year mean FRI of red fir, may not show greater carbon stocks post fire after a fuel treatment.

A more refined analysis could incorporate a life-cycle approach by monitoring carbon that is removed from the forest, the carbon that is emitted by machinery used to treat the forest and employed during fire suppression, the emissions from prescribed fire, the fate of the woody products removed from the forest, or the emissions from dead trees killed by the fire (Earles et al. 2012; Kashian et al. 2006; Winford and Gaither 2012). It could also integrate this information with more comprehensive efforts to develop GHG accounting frameworks to sequester carbon and reduce emissions from forests. Additional research into the decomposition rates of the vegetation types in the Mokelumne watershed could provide some insight into how fast fire-killed trees decompose, thereby increasing the carbon benefits of fuel reduction due to the reduced fire severity and reduced tree mortality (North and Hurteau 2011). Additionally, tracking the biomass removed from treatment, its end uses and longevity, as well as the carbon that could be sequestered by the sites post fire, would allow for a full life-cycle analysis of the carbon impact of fuel treatments. This sort of life-cycle analysis is possible, though it is difficult to accomplish at the scale of the entire Mokelumne watershed without more specific data on the current vegetation. Site-specific assessments that record fire probability and fire severity along with pre- and posttreatment biomass quantities, and that follow the fate of the removed material, would be more feasible and would help refine the answers given in this report.

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Chapter 9: Climate Change Vulnerability Assessment

9.1 Introduction

The fire and sediment modeling conducted as part of this analysis rely on historic datasets of local climate and fire behavior. However, there is significant regional, national, and global evidence that recent historic climatic conditions may not be representative of climate conditions in the next century as a result of greenhouse gas (GHG) emissions leading to rapidly increasing atmospheric CO_2 levels (ICLEI 2007). Future climatic conditions depend heavily on future GHG emissions, which are unknown, and therefore the associated impacts are difficult to predict. The observed fluctuations in both fire behavior and climate patterns over the past decade suggest that climate change has already begun, and the effects felt to date are likely the beginning of greater impacts to come.

Appropriate forest management is a decadal process and planning today's management strategies based on estimated stand conditions is critical to success. This, in combination with a need to better understand the impacts of climate change on ecosystem services and our ability to minimize those impacts, led us to perform a climate change vulnerability assessment for the Mokelumne watershed. The assessment relies on a compilation and review of scientific literature and an analysis of the available climate change projection data relevant to the area. The climatic and hydrologic changes are then applied to a collection of potential climate change impacts to determine where a fuel treatment program would be most effective. The assessment process we used is based on the ICLEI (2007) Climate Change Guide for Local Governments.

Future climatic forecasts are the result of anticipated changes in atmospheric conditions that result from GHG emissions scenarios. These scenarios are used in a suite of Global Circulation Models (GCMs), two of which we focus on in this chapter: the Parallel Climate Model (PCM) and the Geophysical Fluid Dynamics Laboratory (GFDL) Model. Hydrologic variables are projected to change in the future as a result of the combined changes in air temperature and precipitation patterns. A series of expected climate change impacts that realistically may be mitigated by fuel treatments in the Mokelumne watershed were the focus of this analysis, based on the compilation of available local and regional scientific literature.

The projected changes in climate and hydrologic variables are defined in Table 9.6 and Table 9.7, along with a relative confidence rank, supporting evidence, and descriptions of seasonal and spatial patterns, as applicable. The specified confidence level for climate and hydrologic variables is based on agreement between climate model outputs via analysis of climate change projection data available for the Mokelumne region (data available at www.caladapt.org) and an assessment of climate change studies published in the scientific literature. A series of expected climate change impacts relevant to forest, grassland, riparian, and infrastructure were identified from regional studies, with a focus on impacts for which an effective fuel treatments program could reduce the frequency and severity. Some climate change impact information relevant to the Mokelumne watershed was not available or accessible within the scope of this research, so we provide a relative measure of confidence for each vulnerability determination based on the criteria described in Table 9.1. A comprehensive list of references for this vulnerability analysis is provided at the end of the chapter.

9.2 Vulnerability Assessment Methods

Vulnerability is determined by reviewing current conditions, stressors, and the likely extent and magnitude of impacts in the region, and is based on the Integrated Regional Water Management (IRWM) checklist (DWR 2011). Climate change impact projections are often based on detailed numeric models of complex systems that use climate projections as inputs (e.g., hydrologic, ecologic, vegetation, fire). These impacts are combined with regional climate projection data and local information (e.g., topography, land use, crop values, water supply source, water quality) to form the basis for determining sensitivity and adaptive capacity. In turn, sensitivity and adaptive capacity are used to define vulnerability. Determining the sensitivity, adaptive capacity, and therefore the vulnerability of a natural system component requires a degree of subjectivity largely based on the availability of relevant literature and an understanding of cause and effect processes as they pertain to future conditions. To minimize the degree of subjectivity, we used a relative scale (from low to high) and a standardized assessment process that provides reasonable precision and accuracy. The steps taken to complete the vulnerability assessment are described generally in the sections below.

9.3 Climate Change Projections and Emissions Scenarios

Climate science and modeling have historically been limited to global estimations due to the complexities involved with smaller scale estimations. More recently, as understanding of the earth's climate has increased and computer power has advanced, both the science and the models have been applied at smaller, regional scales (e.g., Northern California). There are numerous widely accepted global climate models, each of which focuses on specific physical and chemical processes and interactions that drive climate patterns. Therefore, climate scientists must use multiple models to evaluate the full range of potential future climate patterns and trends, since there is a large amount of uncertainty in our ability to model complex and dynamic systems.

For this assessment, projections of climate and hydrologic changes were drawn from the scientific literature and researched using a suite of different climate models, including the PCM and GFDL models. Climate projections were downscaled by independent studies to better represent future conditions in California and specific regions within the state, including the Mokelumne watershed. The ability to zoom in on California and the Mokelumne watershed was achieved by using Bias Correction and Special Downscaling (BCSD) in several models through emissions scenarios developed by the California Energy Commission (available at www.caladapt.org).

Projections of climate and hydrology changes by global climate models are very sensitive to the future carbon- and/or GHG-emissions scenarios used. Emissions scenarios are plausible estimates of GHG concentrations in the atmosphere at various future years, based on assumptions about future population growth and economic development. The two most commonly used emissions scenarios are the A2 and B1 scenarios, which are widely accepted as the reasonable range of potential future emissions. Scenario A2 assumes that our society will make only minor changes to our current technologies and practices and that GHG emissions will continue to increase at the current rate, leading to an exponential increase in emissions over the next 100 years. B1 assumes a significant global reduction in worldwide GHG emissions, with global carbon emission rates peaking around 2050 and then declining back to the rates of the 1970s. For the majority of references cited in this analysis, the A2 and B1 emissions scenarios are used to bracket the high and low projections. It is possible that our true future emissions will fall somewhere in between these projections.

Climatic model results are expressed through three different measures: the shift in certain climate variables (e.g., mean annual precipitation) over decadal time scales, changes in spatial patterns (e.g., where precipitation falls across a region), and extreme-event changes (e.g., size and frequency). Changes in climate outcomes are determined by factors such as their mean and their variance, which are reported in Table 9.6 and Table 9.7. To estimate future changes in the hydrologic cycle due to climate change, we used the accepted methodology of pairing a hydrologic model with the GCMs, the results of which are reported in Table 9.7. Because of the inherent uncertainty of predicting the future, our climate model outputs have a range of uncertainty and we provide a measure of confidence associated with each projection in Table 9.1. Figure 9.1 compares recent and predicted air temperatures, according to the A2 and B1 scenarios.

Table 9.1: Climate change projections confidence ranking definitions

Confidence ranking	Description
High	General agreement of modeling studies has led to consensus in the scientific literature. Available information is directly relevant and applicable to local systems.
Moderate	Scientifically supported but consensus is not present due to lack of information, moderate differences between studies, or limitations for drawing general conclusions from limited scientific information. Accessibility or application of information to local systems may be somewhat limited.
Low	Limited information or conflicting results between studies, model outputs, or research findings. Accessibility or application of information to local systems is very limited.

9.4 Identifying Impacts

After reviewing the available local and regional scientific literature, we focused on climate change impacts that are both available and relevant to our goal of identifying the potential results of an effective fuel treatments program. These impacts, listed in Table 9.6, Table 9.7, and Table 9.8, are not comprehensive but instead focus solely on wildfire and erosion events.

For the purposes of this chapter, impacts are defined as changes to the condition, function, or structure of natural and human systems in the Mokelumne watershed that result from climate change. Many impacts have already been detected on global and local scales and are expected to continue (Moser et al., 2009). The studies that identify potential impacts of climate change often use the same historic climatic data sets cited in the reporting of climate change projections in Table 9.6, thus supporting the linkages between climate, hydrology, and system impacts delineated in Table 9.6, Table 9.7, and Table 9.8.

9.4.1 Sensitivity

Sensitivity is the degree to which system components (e.g., wildfire regimes, salmonid populations, stormwater conveyance) change due to climate conditions (e.g., temperature and precipitation) or system impacts (e.g., stream temperature increases or snowmelt timing changes). If a system component will be significantly affected by future climate conditions, it is considered to be highly sensitive. Table 9.2 presents the definitions of the sensitivity scale. Factors considered when determining the degrees of sensitivity include:

- The impact's degree of exposure to climate change. For example, coastal areas are more exposed to sea-level-rise-related impacts compared to inland areas.
- The existing stressors in the system beyond climate change, and whether future climatic conditions would exacerbate these stressors. For example, the degree of urban encroachment on forests may be a stressor that promotes greater frequency of wildfire ignitions.
- Resources that may become increasingly limited, either through increased demand or reduced supply, due to climate change.
- Physical and environmental barriers that may limit the ability of a species to adapt. For example, an alpine tree's ability to adjust to warmer temperatures can be limited by elevation if it currently exists at a high elevation.

Table 9.2: Scoring definitions for sensitivity to climate change impacts

Sensitivity	Definition
High	System components are expected to respond measurably to an impact based on historical observations or modeling studies.
Moderate	The response of system components to an impact has not necessarily been measured, but based on our understanding of system function there are likely to be direct or indirect responses and it is reasonable to assume that the sensitivity is not low.
Low	System components not measurably affected by impacts and will likely not be affected by climate change.

9.4.2 Adaptive capacity

As described above, evaluating the adaptive capacity of a system is the second component to understanding the degree to which it can withstand climate change. Adaptive capacities for both natural and human systems were assessed for this analysis. To understand the adaptive capacity of natural systems, we assessed the intrinsic ability of system components to adapt without any human intervention, such as policy or management action changes. For assessment of human/economic systems, adaptive capacity assessment can include the timeframe and cost associated with actions to increase the ability to withstand climate change. In determining how adaptive a system is to climate change, the following elements are considered:

- Current level of stressors and flexibility to respond to future stressors. Has the system component adapted to historic climatic changes or inclement conditions?
- Are there any barriers (legal, physical, biological) to the system's ability to adjust in response to climate change?
- Can the system adapt quickly enough to survive the climate change expected over the next century?
- Are efforts currently underway that would increase adaptability (e.g., water conservation)?

Table 9.3: Scoring definitions for adaptive capacity to climate change impacts

Adaptability	Definition
High	System components are expected to accommodate climate changes.
Moderate	The system has some capacity to adjust and the degree of negative consequences will depend on the magnitude of individual and cumulative impacts.
Low	The system has little or no capacity to accommodate change.

9.4.3 Vulnerability

Vulnerability is a system component's susceptibility to harmful impacts due to climate change. The vulnerability of systems to specific climate change impacts is determined by combining sensitivity and adaptive capacity (see Table 9.4). System components that have high sensitivity to climate changes and a low capacity to adapt are considered to be highly vulnerable to climate change. A system component that is not sensitive to climate change but has a low ability to adapt is considered moderately vulnerable. A highly sensitive impact with a high adaptive capacity suggests that an effective fuel treatment could reduce the associated impacts to upland and riparian habitats.

Table 9.4: Vulnerability ranking matrix

		Sensitivity		
		High	*Moderate*	*Low*
Adaptive capacity	*High*	Moderate	Low	Low
	Moderate	High	Moderate	Low
	Low	High	High	Moderate

The vulnerability scores for each impact are limited by the available science and the body of information used to score sensitivity and adaptive capacity. The determinations for sensitivity and adaptive capacity include subjective evaluations and depend on the perspective by the evaluator. Therefore, our confidence in the vulnerability of each impact is also provided to put bounds on the strength of the conclusions as defined in Table 9.5.

Table 9.5: Scoring definitions for confidence of vulnerability

Confidence ranking	Description
High	General scientific agreement on the vulnerability score; the evaluation is supported by a breadth of monitoring data, modeling results, research, or best available scientific information. Available information is directly relevant and applicable to local systems.
Moderate	Scientifically supported but consensus or agreement is not present due to a lack of information and/or moderate differences between studies. Accessibility or application of information to local systems may be somewhat limited.
Low	Limited information or conflicting results between studies, model outputs, expert opinions, and/or research findings. Accessibility or application of information to local systems is very limited.

Table 9.6: Projected changes for selected climate variables in the Mokelumne watershed

Climate variable (30 yr. intervals)	*Projected change by 2100*	*Confidence ranking*	*Supporting evidence*	*Seasonal and spatial patterns*
Average annual air temperatures	Expected to increase 2.5-7.5°C above historic reference period of 1971-2000	High	Projections generally show agreement between models (data downloaded from Caladapt 2013) and are consistent with statewide projections (Cayan et al. 2009). Temperature ranges correspond to different emissions scenarios and locations within the watershed.	Projections indicate longer summers with increases of 3-9°C. Winter temperature increases are projected to be slightly lower at 2-6°C (Cayan et al. 2009).
Air temperature variability	Expected 20-30% larger standard deviation than the historic reference period of 1971-2000	High	Projections generally show agreement between models (data downloaded from Caladapt 2013) and are generally consistent with statewide projections (Cayan et al. 2009).	Increases are projected in the frequency, magnitude, and duration of heat waves (temperature that exceeds 95th percentile of region's historic record). Typically, heat waves occur in July and August, but as temperatures increase over time, heat waves are expected to occur in fall and spring months with greater frequency (Cayan et al. 2009).
Annual precipitation totals	Direction of change undetermined	Low	Climate models disagree on the directional impact of climate change on precipitation (Caladapt 2011). PCM climate models generally suggest higher annual precipitation, while GFCL models indicate less rainfall, with disagreement on which months are responsible for annual precipitation increases (Cayan et al. 2009; Thorne et al. 2012).	Total annual precipitation changes cannot be determined; however, models project less precipitation in the fall and spring, meaning a majority of the precipitation will be delivered over a shortened winter season (Cayan et al. 2009; Thorne et al. 2012). Summers are predicted to be longer and drier, while peak annual precipitation appears to shift from January to February (Flint and Flint 2012).
Precipitation variability	Direction of change undetermined	Low	Climate models disagree on the direction of change. Models indicate a high degree of inter-seasonal variability, not significantly different than the historical record and without a consistent trend for the next 100 years.	Models agree the wet season, when the predominant amount of rainfall occurs, will be shortened. Some models indicate a decrease in the annual storm count but an increase in the amount of precipitation delivered per storm (Cayan et al. 2009). Potential increase in the number of storms as well as above average rainfall has been predicted for elsewhere in the state (Flint and Flint 2012). Different climate models and scenarios consistently show reductions in May precipitation totals in the Mokelumne (data downloaded from CalAdapt 2013).

Table 9.7: Projected changes for selected hydrologic variables of the Mokelumne watershed

Hydrologic variable (30 yr. intervals)	*Projected change by 2100*	*Confidence ranking*	*Supporting evidence*	*Seasonal and spatial patterns*
Drought	Approximately 50% increase in frequency of occurrence	High	Climate models agree that precipitation will be highly variable and that a drying trend is anticipated mid-century, resulting in vulnerability to drought (Cayan et al. 2012).	Future projections indicate an increase in frequency of drought; GFDL-A2 models estimate that there will be 6 droughts over the next 70 years, followed by a multi-decadal drought at the end of the century. PCM-A2 models suggest 8 droughts over the next 90 years (Flint and Flint 2012).
Potential evapotranspiration (PET)	Increase (25-70 mm) above historic reference period of 1971-2000	High	Warming average temperatures suggest increases in annual PET. Statewide models agree in the increasing change of direction in PET (Thorne et al. 2012).	Largest changes are projected during summer months (Thorne et al. 2012).
Groundwater recharge	Decrease (6-140 mm) below historic reference period of 1971-2000	High	Statewide models agree that there will be a decrease in groundwater recharge. The prediction of decreased recharge is identified by studies that predict either an increase or a decrease in future runoff (Thorne et al. 2012).	Shorter wet seasons and earlier snowmelt, coupled with longer, drier summers and increased PET, will produce unfavorable conditions for recharge. Peak recharge shifts from January to February, with the largest recharge decrease anticipated to occur in the fall (Flint and Flint 2012).
Snowpack	Decrease (7-17mm) in April above 8000 ft.	High	Snowpack decreases are directly tied to temperature increases. As temperatures warm, snow accumulation, persistence, and volume will decrease, regardless of precipitation projections. Models and emission scenarios predict reductions of 25-90% of snow water equivalent (SWE) in the Sierras by the end of the twenty-first century (Hayhoe et al. 2004).	Snowpack changes at higher elevations draining to the Mokelumne River will primarily affect the watershed via runoff pattern changes in the spring and summer (Table 9.2). March temperatures will reduce the amount of precipitation that falls as snow (Knowles et al. 2006). Increased precipitation as rain versus snow paired, with warmer temperatures from April to June, will shift peak snowmelt to earlier in the season (Knowles et al. 2006).

Runoff variability	Increase	Low	Modeling in Northern California indicates a possible increase in the largest 10% of flows above the historical period, but ambiguous change for other percentile flow ranges (Flint and Flint 2012).	Different climate models and scenarios consistently show reductions in May precipitation totals in the Mokelumne watershed, but what the resulting impact in May runoff will be is not fully understood (CalAdapt 2011).
Annual runoff	Undetermined	Low	PCM models predict an increase in precipitation, while the GFDL model forecasts a drying trend. Runoff predictions are tied to conflicting precipitation models; as a result, PCM models predict a large increase in runoff volumes in the region while the GFDL predicts a decrease (Thorne et al. 2012). Runoff modeling by Null et al. (2010) indicates there may be between a 6.4% and 9.4 % increase in the mean annual runoff as a result of air temperature increases. The Mokelumne watershed was shown to be one of the two most sensitive in the region with respect to changes in mean annual flow, peak annual flow, and duration of low flows (Null et al. 2010)	Peak runoff has traditionally been observed during snowmelt periods, typically between April–July in California. As temperatures increase, snowmelt and peak streamflow will shift to earlier in the year (Thorne et al. 2012). Shifts to the mid-point of annual runoff timing (date by which half of the annual runoff has occurred) may be 5-6 weeks earlier in the year, coupled with a 6-9 week increase in low flow durations during the summer and fall (Null et al. 2010).

Table 9.8: Vulnerability assessment for Mokelumne watershed wildfire climate change impacts, with expected adaptation benefits of an effective fuel treatment program

Expected Impact	*Climate drivers and stressors*	*References*	*Sensitivity*	*Adaptive capacity*	*Vulnerability*	*Vulnerability confidence*	*Can the expected impact be lessened by an effective fuel treatments program?*
Increased wildfire frequency and extent	Increased air temperatures, longer summers, increased PET, increased drought frequency and persistence, earlier snow melt.	Fried et al. 2004 FRAP 2010 Flannigan et al. 2000 Westerling et al. 2006 Westerling and Bryant 2008 Lenihan et al. 2008	High	High	High	High	YES Local fire modeling indicates a significant reduction in wildfire frequency and extent can be achieved through a fuel treatments program. (See Chapter 3)
Increased wildfire intensity		Fried et al. 2004 FRAP 2010 Flannigan et al. 2000 Westerling et al. 2006 Westerling and Bryant 2008 Lenihan et al. 2008	High	High	High	High	YES Local fire modeling indicates a significant reduction in wildfire intensity in high-risk locations. (See Chapter 3)
Increased costs of fuel treatment and fire suppression		Joyce et al. 2008 Thompson et al. 2012 Prestemon et al. 2012	High	Moderate	High	Moderate	YES Increasing wildfire risks and human encroachment into forested areas results in increased costs to forest managers to minimize ignitions and damage from fires. Local fire modeling indicates the frequency, extent, and intensity of fire can be significantly reduced.
Increased tree mortality	Increased drought frequency and persistence, insect infestations, disease, wildfire regime shifts	Hansen and Weltzin 2000 Shugart 2003 Barr et al. 2010 Hood et al. 2010	High	Moderate	High	High	YES Expected impact is driven by over-dense forests; fuel treatments reduce vegetation density in lieu of regular fire occurrence.
Reduced conifer timber harvest		Hannah et al. 2011	Moderate	Moderate	Moderate	Moderate	MAYBE Timber is a critical agricultural industry in the Mokelumne watershed and strategic fuel treatments may reduce wildfire damage to future harvest trees.

Shift from needle-leafed to broad-leafed trees	Increased drought frequency and persistence, insect infestations, disease, wildfire regime shifts	Lenihan et al. 2006 Lenihan et al. 2003 FRAP 2010 Lenihan et al. 2006 PRBO 2011 Lenihan et al. 2008 Barr et al. 2010	Moderate	Moderate	Moderate	Moderate	MAYBE Vegetation pattern shifts are partly due to changes in fire disturbance, but temperature increases and other associated impacts and stressors are important drivers.
Conversion of shrublands and woodlands to grasslands		FRAP 2010 Pierson et al. 2008 Lenihan et al. 2006	Moderate	Moderate	Moderate	Moderate	
Increased flooding risk	Rainfall pattern shifts, increasing encroachment to wildlands	Moody et al. 2008 DeBano 2000 Benavides-Solorio and MacDonald 2005	Low	High	Low	Low	YES Increases in flood risk are directly associated with wildfire occurrence due to loss of infiltration and increased runoff. Fire severity and other fire related impacts can be reduced with fuel treatments.
Increased sediment loading to streams and reservoirs from erosion, landslides, and debris flows	Wildfire regime shifts, rainfall pattern shifts	Paris and Cannon 2012 DeBano 2000 Thompson et al. 2013	High	Moderate	High	High	YES Sediment loading risks are associated with wildfire regime shifts. Local fire and sediment modeling suggests a significant reduction in landslide, debris flow and hillslope erosion as a result of effective fuel treatments.
Increased risk of property and infrastructure damage	Increased drought frequency and persistence, continued fire suppression actions.	Moritz and Stephens 2008 Jones and Goodrich 2008 Laird 2013 Scott et al. 2013	High	Moderate	High	Moderate	YES Future population increases will increase encroachment to forests and greater damage with increasing wildfire risks. Land-use planning policies and an effective fuel treatments program could reduce structure loss from wildfires.

Reduced habitat extent and quality for endemic fish, amphibian, and invertebrate species	Increased droughts, reduced groundwater recharge, increased stream temperatures, loss of riparian cover, earlier snow melt, reduced summer baseflows.	Moyle et al. 2012a Moyle et al. 2012b Ekstrom and Moser 2012 PRBO 2011 NMFS 2012 Medellín-Azuara et al. 2008 Barr et al. 2010 NCIRWMP 2007	High	Low	High	High	NO Conflict between water supply, hydroelectric power, and instream habitat for aquatic species will increase in the future, as will other climate-related habitat stressors. Fire-related damage to the riparian zone can result in long-term impacts to habitat quality. Some aquatic species, including salmonids, require a narrow water temperature range, which is directly correlated to air temperatures.
Decreased terrestrial cold-water fish yields		Knapp et al. 2001 Pope et al. 2009 Moyle et al. 2012a Moyle et al. 2012b NMFS 2012 Barr et al. 2010 Medellín-Azuara et al. 2008	High	Low	High	Low	NO Fire-induced erosion will degrade spawning grounds of native fish such as lamprey, suckers, salmon, and trout that build their nests in areas of clean rocks and gravels. While fuel treatments could directly reduce wildfire-induced sediment delivery to local fisheries, other climate-related stressors will increase, specifically temperature impacts.

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Chapter 10: Mokelumne Avoided Cost Analysis Conclusion

10.1 Overview

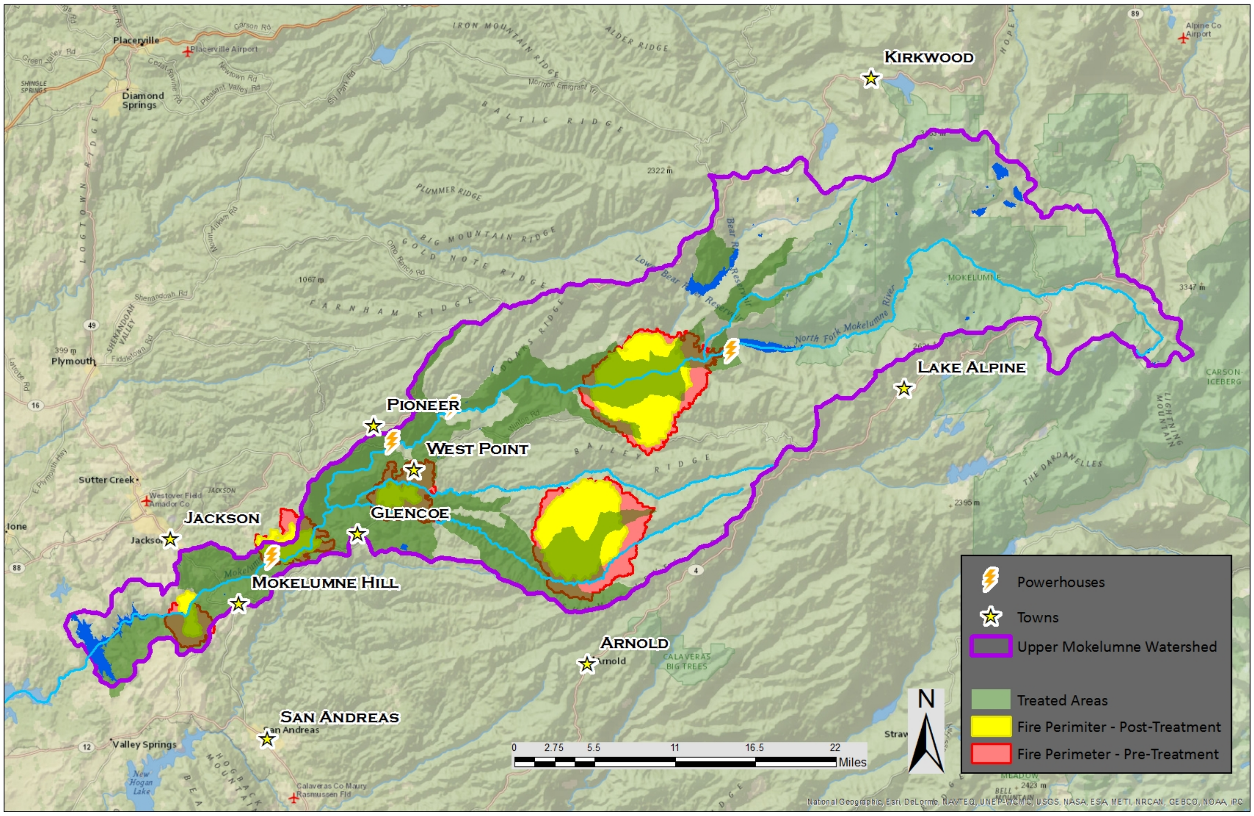
The purpose of this analysis is to evaluate the costs and consequences of wildfire in the upper Mokelumne River watershed with and without fuel reduction treatments. The analysis shows that thinning the forests and reducing hazardous fuels would substantially reduce the probability, extent, and intensity of wildfire in the watershed, leading to quantifiable cost savings. In short, strategic fuel reduction treatments are a good investment and produce multiple benefits to landowners, residents, and watershed interests and beneficiaries.

To evaluate the avoided costs associated with fuel reduction treatments, we identified the types and locations of wildfire fuel treatments that could be used to reduce the probability, extent, and intensity of wildfire in the upper Mokelumne watershed. This treatment strategy for the project area is based on treatments commonly applied by local public land managers. We used the fire model FSim to predict future wildfires in the watershed based on historical patterns and then applied the fuel treatment scenario to the model to identify how wildfire characteristics would change in response. We quantified the financial costs and benefits, including biomass, carbon, and job impacts. It is important to note that because our fire modeling was based on historic fire trends (last 30 years), our conclusions may underestimate the costs and benefits associated with larger, more destructive fires that have become more common in the Sierra Nevada over the last decade and are projected to increase with climate change.

We used the fire simulations to identify the effects of fire directly on assets, including homes, roads, transmission lines, and timber resources. We also estimated the fire suppression costs and carbon emissions, both with and without fuel treatment. We used the GeoWEPP and Debris Flow erosion models to evaluate the effects of fire on sediment erosion, and modeled the transport and impact of that sediment on water storage, diversion, and conveyance infrastructure for the utilities in the watershed. Through these analyses we estimated the value of several important categories of direct and indirect benefits of fuel treatment in the Mokelumne watershed. There are other categories of benefits we do not quantify in this report that are worthy of further future review. These include air quality, water quality, habitat and wildlife, recreation, cultural sites, and other forms of carbon sequestration. There are likely other resiliency benefits as well.

This study shows that the total quantified benefits of fuel treatment would far exceed the costs of treatment if fires occur over the next few decades, which is a strong possibility. The benefits accrue to a wide range of land and water managers and owners, public and private entities, and taxpayers and electric and water utility ratepayers in general. Figure 10.1 shows that not all fuel treatments were within the vicinity of the five fires. This demonstrates that we included the costs for fuel treatments in areas did not directly provide fire protection in our modeled scenario, reflecting the reality that not every treated area will experience wildfire. All told, in this study we found that benefits due to fuel treatments total between $126 and $224 million, and their value is two to three times the costs (Table 10.1 and Figure 10.2).

Figure 10.1: Locations of fuel treatments and fires



10.2 Summary of Fuel Treatment Costs and Benefits

As a first step toward determining the potential costs and benefits of fuel treatments, we first defined a potential fuel treatment scenario, which was reviewed and refined by local land managers so that techniques and costs were consistent with local practices. While a literature review suggests a wide potential range of costs ($17 to $160 million) for our treatment scenario, based on local information we estimate a one-time cost of implementing this scenario of approximately $46 million. This $46 million estimate is based on the closest alignment with our model simulation requirements and based on the assumptions that all treatments occur within one year, and that the treatments cover 100% of the Treated Area Units (TAUs). If we extend the effectiveness of this treatment to the full 30 years that the Five Fire scenario[1] (see Chapter 3) examines, and include the costs for retreatment to maintain the effectiveness of the treatments over that timeframe, the total cost would be $68 million, using a net present cost at a 3% discount rate.

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[1] Based on historical patterns, current fuel loading, and discussions with local and regional fire experts, we teased out five representative fires from the modeling data that represent probable fire locations and footprints over the next 30 years in the Mokelumne watershed. We used this fires scenario to ground the modeled difference in reality and to ascertain the damages and benefits to the area, with and without fuel treatment.

Under normal forest management, large tracts of forested lands are not treated at once as described in our scenario, but rather a portion of an area is treated at a portion of our treatment cost, with a similar end result of reducing wildfire threat and improving forest health. Following discussions with local land managers, we believe that most of the benefits demonstrated by our treatments could be achieved at much less than 100% full implementation (see Chapter 7, Table 7.3). This is because strategically placed treatments can reduce the burn probability of adjacent untreated areas, and the treatment areas provide firefighters a greater chance of slowing or stopping a blaze before it moves into adjacent untreated areas. Based on these estimates, as described in Chapter 7, the treatment costs would drop to $16 million. We show this as the low-cost range in Figure 10.2, as well as including the high-cost range of $68 million described above. Figure 10.2 also shows the multiple benefits and associated savings of fuel treatment, which are outlined below. It is important to point out, however, that the models were run at full implementation levels and therefore the benefits discussed here refer only to a full level of implementation, rather than the reduced level proposed by the land managers. In the end, the results suggest that even the low-end benefit estimates exceed the high-end cost estimates.

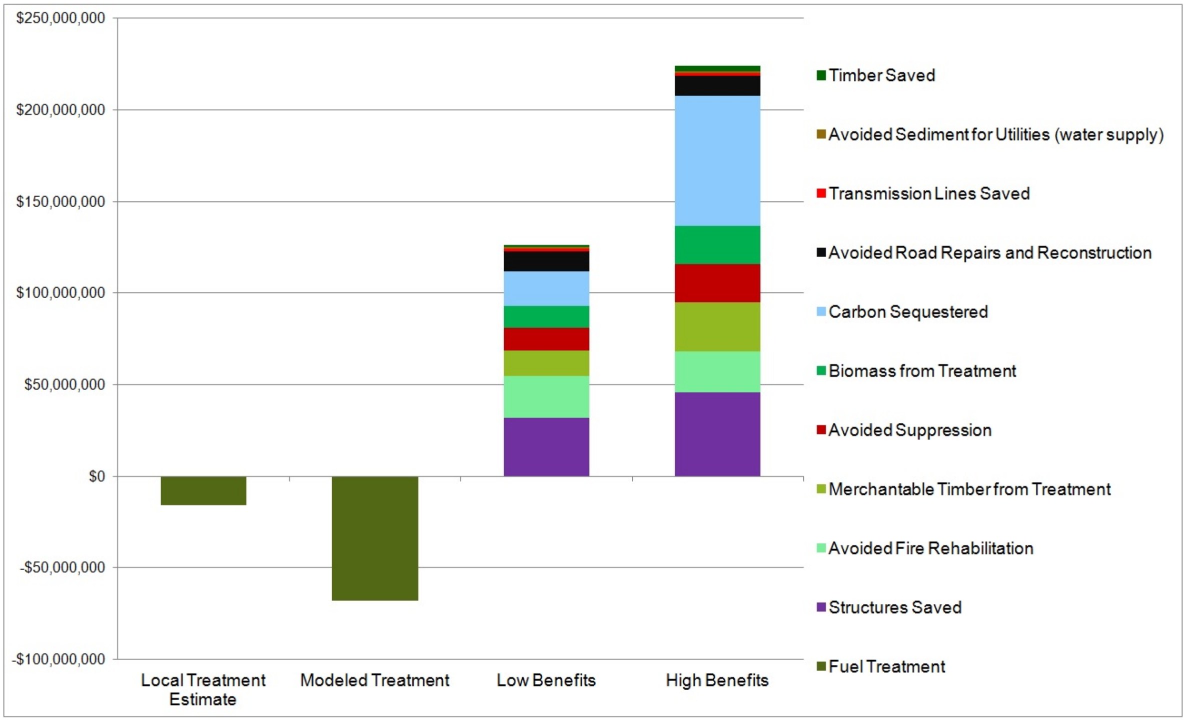
Based on consultation with local Bureau of Land Management (BLM) and U.S. Forest Service (USFS) staff and prevailing market conditions, we estimate the potential revenue from merchantable timber associated with the fuel treatment efforts would be between $14 and $27 million under a 1-year treatment plan. Biomass chip revenue, with sufficient demand, regional bioenergy generation capacity, and value added manufacturing, could reach between $12 and $21 million under the 1-year treatment plan.

The modeled wildfires would immediately damage and destroy infrastructure and assets. Homes, businesses, and other public and private structures would be lost. Not including roads or utility infrastructure, the structures in the areas that would have burned in the Five Fires scenario without treatments are worth $46 million. The change in the value of structures in high- and medium-severity areas of the fires equates to $32 million, providing the range of structural values. While some structures might maintain residual value and only require repairs, others requiring total demolition would have costs greater than simply the replacement construction costs because of cleanup (see Chapter 5). It is also important to note that these costs are based on county assessor data, where values are constrained by Proposition 13, rather than replacement cost values from insurance companies, which could significantly increase the value of the structures saved compared with the constrained assessor data.

For private landowners, parcels zoned for timber that do not burn as a result of treatment have an assessed value of $1.2 million (see Chapter 5). Public lands are managed for different objectives than private timber parcels and it is therefore common to use half of the average hectare value of these parcels to estimate the timber value on public lands. When applied to this study, the result is that treatments helped to protect $1.9 million in public timber values, bringing the total of protected timber resources to $3.1 million. Because the timber on public lands may or may not have ever been removed from the forest, we apply its value only to the high benefit side of the avoided costs, while protected private timber values are placed in both the low and high benefit categories. We estimate road repair and reconstruction costs avoided to be $10.6 million.

Additionally, the cost savings from avoiding the repair and reconstruction of transmission lines based on this scenario would be $1.6 million (see Chapter 5).

Figure 10.2: Low and high range of fuel treatment costs and total quantified benefits



We estimate fire suppression cost savings to range from $12.5 to $20.8 million, and associated postfire recovery cost savings to be $22.5 million (see Chapter 4). The avoided carbon emissions for fuel treatment and reduced fire acreage ranges from $19 million, based on current market prices in California, to $71 million when factoring in the social cost of carbon (see Chapter 8). The social cost of carbon does not yet reflect a revenue opportunity, but because of the high importance the State of California places on climate change and associated regulations to reduce greenhouse gas (GHG) emissions, we believe it is relevant to show this value. Cost savings for utility operations in the upper Mokelumne, based on the potential lost storage for water supply and discounted over 30 years, would be an estimated $1 million (see Chapter 6). We do not include values for other potential effects on storage or disruptions in conveyance for electricity generation; see Chapter 6 for a discussion of potential risk in these areas.

All told, the benefits we accounted for in this study due to fuel treatments total between $126 and $224 million (Table 10.1). If the fires were to occur one year after the treatments were implemented, the benefits specific to avoided fire damage would be pushed back by one year, leading to discounting (3%) and a shift in the benefit range down to $122 to $218 million. Under either case, the quantified benefits are two to four times the costs (Figure 10.2). If the fires were to occur in the tenth year after treatments, the discounted present value of the treatment would be $106 to $197 million ($86 to $173 million at 7%), accounting for the delay in avoided costs inherent with the unpredictability of when severe fires would occur.

Table 10.1: Total costs and benefits for fuel treatment scenario

Costs		
Fuel Treatment	$16,000,000	$68,000,000
Benefits	*Low*	*High*
Structures Saved	$32,000,000	$45,600,000
Avoided Fire Cleanup	$22,500,000	$22,500,000
Carbon Sequestered	$19,000,000	$71,000,000
Merchantable Timber from Treatment	$14,000,000	$27,000,000
Avoided Suppression	$12,500,000	$20,800,000
Biomass from Treatment	$12,000,000	$21,000,000
Avoided Road Repairs and Reconstruction	$10,630,000	$10,630,000
Transmission Lines Saved	$1,600,000	$1,600,000
Timber Saved	$1,200,000	$3,130,250
Avoided Sediment for Utilities (water supply)	$1,000,000	$1,000,000
Total Benefits	*$126,430,000*	*$224,260,250*

Note: Values rounded to significant figures.

Avoided postfire sediment for water and power utilities, based on the fire conditions we modeled, represent approximately 1-2% of the total calculated avoided costs, a result that is significantly lower than what occurred in the Denver area. The difference in our results is likely attributable to site-specific factors such as the water infrastructure and erodibility of the soils within the Mokelumne watershed. Large water storage reservoirs in the Mokelumne watershed dilute the effect of sediment on water storage capacity, in comparison to the Strontia Springs Reservoir in Colorado, where the postfire erosion costs were very large because of the need for reservoir dredging and emergency alternative water supplies. The capacity of Pardee Reservoir in the Mokelumne watershed is 210,000 acre-feet, or 30 times larger than Strontia Springs Reservoir (7,000 acre-feet), which plays a crucial role in Denver's water supply storage, similar to the Mokelumne's significance to the East Bay.

As this study shows, Pardee Reservoir will not lose a significant percentage of water storage capacity from the modeled postfire sediment given the ratio of reservoir capacity to sediment volume. This report's release during the worst drought year on record, however, highlights the importance of every acre-foot of potential storage, even if that acre-foot is a small percentage of total capacity. Additionally, soil erodibility in the Mokelumne watershed is significantly less than in other areas in California and the western United States, where the risk of postfire erosion is far greater (e.g., due to decomposed granite soils). Application of this study design to a watershed with more erodible soils and smaller reservoir storage would likely result in avoided erosion costs representing a larger percent of the total avoided cost. There is potential for water quality effects that would disrupt supply or increase treatment costs for EBMUD, but this analysis was not included in this report.

The project team needed to prioritize values and resources to keep the project manageable, both in scale and budget, and therefore chose to not include a wide range of ecological and cultural values, including value of habitat and cultural resources lost, water contamination other than sediment, air quality, lost tourism/recreational opportunities and access, and spoiled scenic views. We also did not address human health and risk, particularly in the path of a major wildfire and its smoke plume. Our study did not consider potential increases in water yield that may result from forest thinning, such as from increased snowpack accumulation under less dense canopies, a process under active study. There might also be changes in natural runoff patterns that exacerbate water storage constraints. There are likely other losses to property value beyond structures and timber, either through direct effects or regional degradation. And there are other losses of ecosystem services provided by these forests and streams, such as support for nutrient cycles or other ecological processes that cross the watershed boundary. A full accounting of all these impacts and costs would have increased the total avoided costs that would result from fuel reduction treatments. A recent study by Earth Economics, commissioned by the San Francisco Public Utilities Commission, estimated habitat values lost to the Rim Fire based on literature averages by habitat type, which occurred in the Tuolumne River watershed near the Mokelumne. Of the ecosystem services they evaluated, they estimated the habitat-based values lost, beyond suppression and infrastructure costs, to be over $100 million in the first year alone, although these costs are not market based[2].

To remain within the project budget and timeline, limitations also needed to be made to the modeling effort, primarily the limit of running only one treatment scenario. Land managers typically do not have access to multiple iterations of modeling in their project planning process to determine where fuel reduction treatments would have the greatest impact based on costs and benefits; the modeling for this analysis did not include multiple scenarios either. Therefore, there was no opportunity to consider the best locations to model fuel reduction treatments to maximize avoided costs. We also based wildfire risk on the historical fire record; however, as the Rim Fire and other recent conflagrations show, there are larger and higher intensity wildfires occurring today than in the past. As a result, the historic context of our wildfire modeling may have underestimated the scale of future wildfires in the watershed. We attempted to address this limitation with the climate change scenario and by modeling five fires, yet even these fires are considerably smaller in area than the Rim Fire footprint (Figure 10.3). In short, the magnitude of the wildfire risk today may be outside of the range that we could model and predict based on the historic record, and as a result our avoided costs and benefits may be similarly underestimated.

This study was designed to model fuel treatments that would address a subset of economic, ecological, and social goals; it is not intended as a land management plan for the Mokelumne watershed. Our analysis focuses on areas in the watershed at high risk of wildfire, associated postfire sediment, and assets at risk to burn, and as such it may help land and water managers identify future priority areas for fuel reduction. It uses sophisticated wildfire and postfire erosion risk modeling that was previously unavailable. The study can potentially be useful for multiple purposes, including supporting the California Department of Water Resource's State Water Plan

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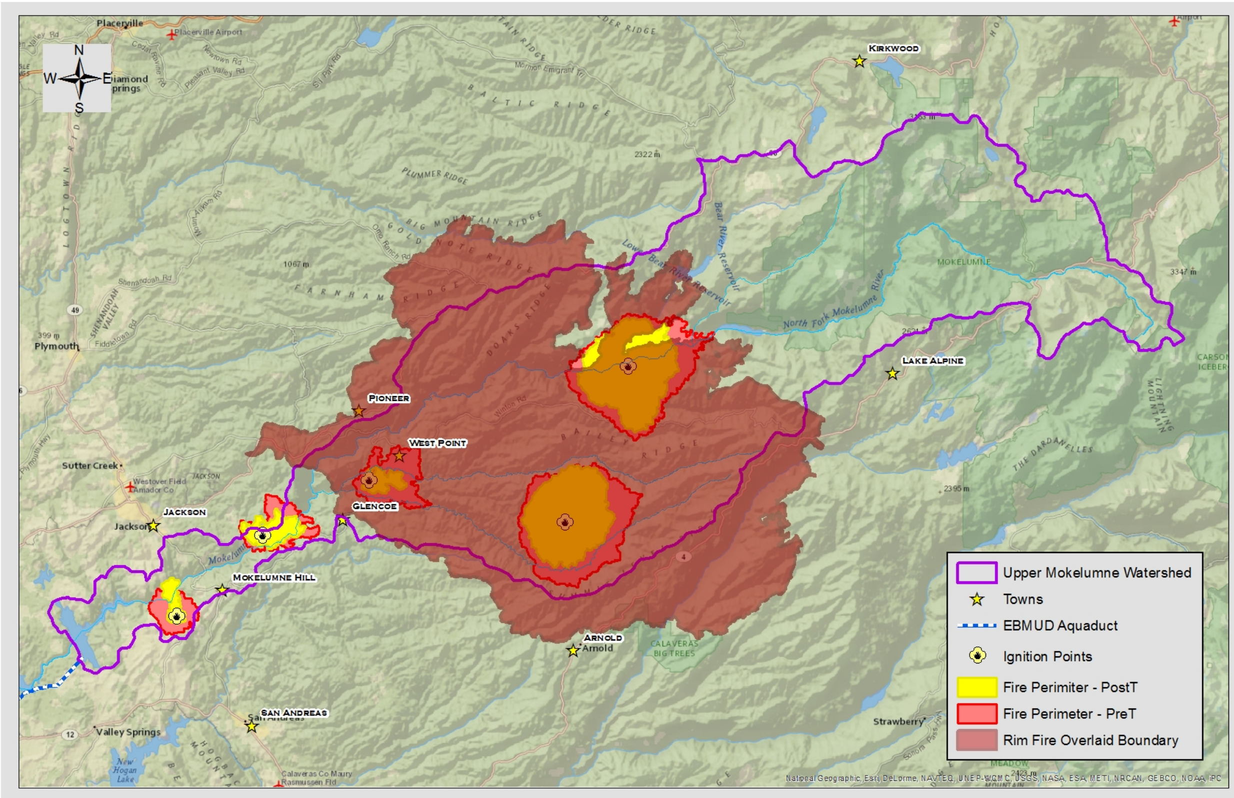
[2] Earth Economics. 2013. "Preliminary Assessment: The Economic Impact of the 2013 Rim Fire on Natural Lands." http://www.eartheconomics.org/FileLibrary/file/Reports/Earth%20Economics%20Rim%20Fire%20Report%2011.27.2013.pdf

updates and the Integrated Regional Water Management planning efforts, as well as informing land and water management planning at the federal, state, utility, and private level.

Figure 10.3: Rim Fire boundary overlaid on Mokelumne watershed and Five Fires scenario



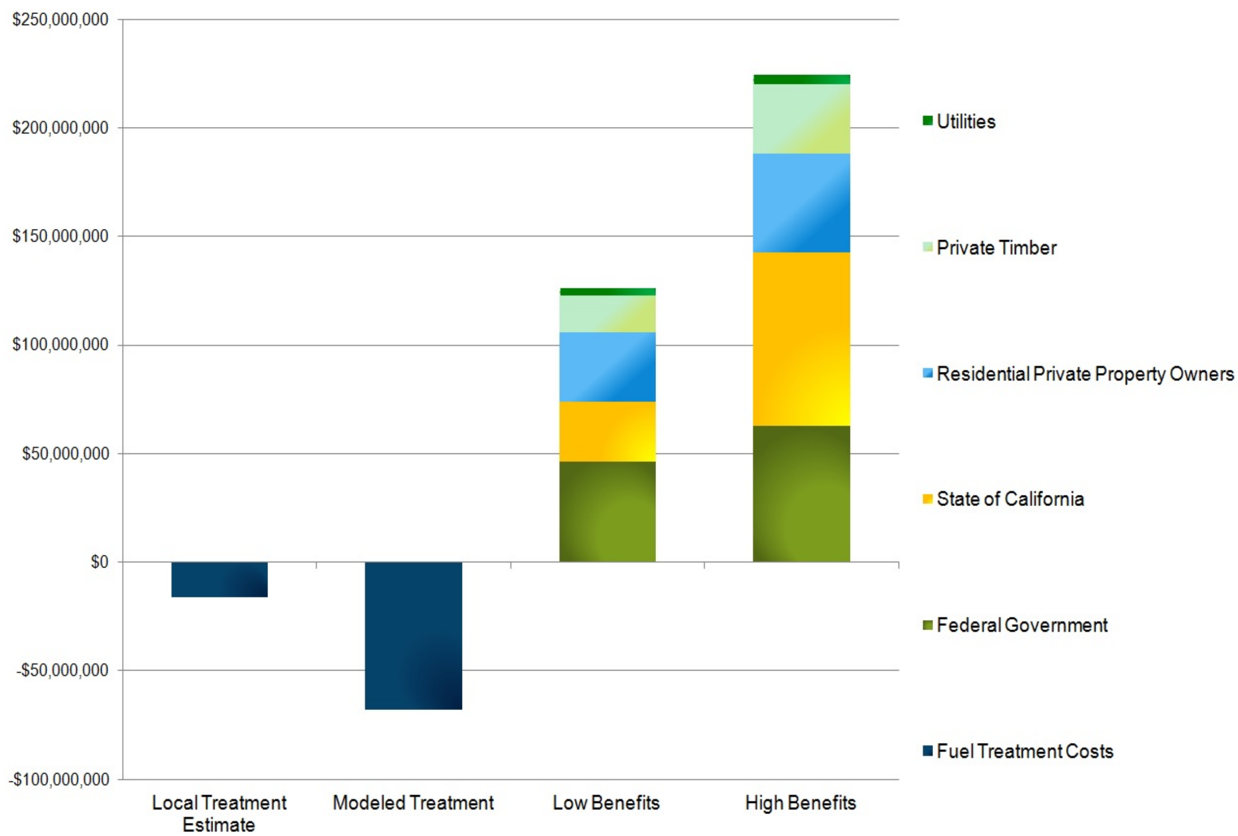
The scale of modeled treatments in this study is considerably larger than either those proposed by the Amador Calaveras Consensus Group (ACCG), a local forest collaborative, or those that are currently being implemented by land managers. Increasing fuel reduction efforts to the pace and scale herein would require additional funding as well as building infrastructure, such as appropriately scaled bioenergy facilities or value added manufacturing to use the biomass generated. Until an adequate amount of infrastructure is established, it could also require that air quality regulators allow more burn days to open pile burn the higher volume of material generated with this scenario. Each local land manager may have priorities that differ from those at the core of this study and therefore their priority areas may lie outside of our treatment areas. Implementation in other areas could be constrained by factors that fell outside of the purview of this analysis.

10.3 Distribution and Management Implications

This study suggests that the total quantified benefits of fuel treatment would very likely exceed the costs of treatment if fires occur over the next few decades, which is a strong possibility. These benefits accrue to a wide range of land managers and owners, public and private entities, and taxpayers and ratepayers in general. We aggregated benefits from Table 10.1 by beneficiary to develop Figure 10.4. It was not feasible to identify the precise breakdown of all benefit categories, but we did so where the data allowed. For example, we allocated biomass and merchantable timber benefits from fuel treatment by the breakdown of landownership within the treatment footprints, with roughly 36% federal and 64% private (see Table 2.1 in Chapter 2). And while the beneficiaries of carbon sequestration or carbon credit sales would be quite broad, we allocate these benefits to the State of California given the State's climate GHG emission reduction goals and regulations. We also assume the road repair costs would primarily accrue to the state, although some private, county, and federal forest roads would also require repair and reconstruction.

As we show in Figure 10.4, the primary beneficiaries from our modeling scenario results are the State of California, the federal government, private property owners and insurers, and timber owners. In addition to the protection of its timber assets, the federal government would also see substantial benefits through avoided fire suppression and recovery costs. Relative to overall benefits, the utilities' benefits from our modeling scenarios are relatively modest, but the utility companies acknowledge the value of reducing direct risk from fire to structures and transmission lines, as well as disruptions in operation.

Figure 10.4: Fuel treatment beneficiaries



Note: Private timber by itself refers to lost private timber due to fire, while the combined public and private timber category includes other forest product resources that generate revenue from a mix of public and private lands, and are not easily disaggregated.

This analysis demonstrates that the benefits associated with fuel treatments in high-risk areas can greatly outweigh the status quo and that the benefits received are spread among a broad range of stakeholders. The work also shows that the costs and benefits are not limited to the geographic area of the burn perimeter, but instead have far-reaching consequences. Californians in general benefit from many of these categories. Additionally, there are a large number of environmental benefits, environmental services, and cultural resources that we were not able to evaluate in this analysis. These cost/benefit categories, such as recreation, air quality, snowpack protection, and wildlife habitat, would yield even more regional, statewide, and even global, benefits. Several ongoing studies of the benefits of fuel treatments for snowpack accumulation and water storage suggest natural water storage benefits, especially when compared to areas burned at high severity. The hypothesis is that fuel treatments, especially in high-severity burn risk areas, lead to more water accumulation (in the form of snowpack and soil infiltration) and delayed snowpack release (thus occurring during California's dry months).

Our analysis demonstrates that the federal government has the potential to benefit from a wide array of avoided costs, which would protect its revenue opportunities in the form of biomass and timber. Private timber assets are extensive in the fire footprint areas as well. While the overall share of benefits accruing to utilities in this particular watershed is proportionally low, the risk of disruption in water supply can have impacts that might be considered more important than their quantified market effects.

The costs/benefits studied here were based on one set of fire and climate conditions, using historical data, with the goal of helping us better understand the relative scale of risks and benefits. Unfortunately, the Rim Fire teaches us that historical patterns may not be the best guide for future events and our results should be weighted accordingly. Further efforts could focus on re-running the models to factor in expected changes in both climate and fire patterns, which would also help test the robustness of various treatments in the face of more extreme events. Postfire observations in both the American and Rim Fire burn perimeters suggest that fuel treatments may maintain their effectiveness even under more dire circumstances than we considered in this study, which substantially adds to their value.

It is also important to remember that local land and water managers have their own management needs that take top priority, especially as budgets grow ever tighter, and their needs may not overlap with the needs of those outside their property lines. Public lands and natural resources have always provided a diverse set of benefits to the general public as a whole. Reducing the risk of uncharacteristic, catastrophic wildfire creates a similar diverse set of benefits, where a large-scale investment would generate substantial returns.

The challenge of differing levels of risk and expectations, combined with opportunities to benefit from treatment activities undertaken by others, suggests a need for a broader-level effort to ensure the development of sustainable approaches to treating wildfire fuels in the upper Mokelumne watershed. The scale of benefits relative to the costs suggests that society may be well served by implementing fuel treatments. The broad diffusion of benefits accounted for in this study demonstrates the need for a similarly diverse set of stakeholders to finance and implement the treatments. This broad coalition of investors, working with local land managers and local interests, could yield a large return on their investments.

Appendix A - Fire Modeling

A.1 Assessing Wildfire Hazard

Hazard is a physical situation with potential for causing harm or damage. Wildfire hazard can be quantified by combining the likelihood of experiencing a wildfire with the intensity, or severity, of that wildfire if it were to occur. Two geospatial fire modeling systems—FSim and FlamMap5—were used to quantify wildfire hazard in the Mokelumne watershed and the surrounding landscape, in both a baseline (circa 2008) and a hypothetical treatment scenario.

A.1.1 Fire SIMulation system (FSim)

FSim, a large-fire simulator, was first developed for the Fire Program Analysis (FPA) project (http://fpa.nifc.gov/). FSim is a comprehensive, stochastic fire ignition, growth, and suppression simulation system that pairs a fire growth model (Finney 1998, Finney 2002) and a model of ignition probability with simulated weather streams in order to simulate fire ignition and growth for tens of thousands of fire seasons. The results of these simulations are used to estimate annual burn probability (BP) for each grid cell across a landscape. In FSim, annual BP is estimated by dividing the number of simulated fires that burned each pixel by the total number of simulated fire seasons. We used FSim (Finney and others 2011) to determine geospatial burn probability across the Mokelumne landscape.

In addition to the gridded BP results, FSim also produces an ESRI shapefile containing the final perimeter of each simulated fire. The perimeter results are useful for assessing risk to watersheds. With the perimeters it is possible to calculate the probability of fire reaching any part of a watershed, and the distribution of watershed area burned. Moreover, the fire perimeter results can be combined with gridded fire effects modeling, such as sediment production, and polygon-based fire effects modeling, such as debris flow likelihood and volume, to estimate conditional and expected fire and post-fire effects. FSim's gridded and fire perimeter results have been used for spatial risk analyses in a number of contexts (Scott et al. 2012a, 2012b; Thompson et al. 2011, 2013a, 2013b).

Simulation of daily values of Energy Release Component (ERC) of the National Fire Danger Rating System is the foundation of FSim's operation. ERC is calculated from historical weather data (Cohen and Deeming 1985). The simulated ERC is used in two ways: first, to determine the probability of a fire start for each day, and second, to determine which of three fuel moisture scenarios to use for the day. The three scenarios correspond to ERC classes with breaks at the 80th, 90th, and 97th percentile ERC values. ERC is simulated for each day of each simulated fire season based on the historic seasonal trend in mean and standard deviation of ERC using temporal autocorrelation (Finney *et al.* 2010). Fire growth occurs only on days for which the simulated ERC exceeds the 80th percentile. Simulated fire growth for each day of each fire is also a function of wind speed and direction. Wind characteristics for each day are determined by a random draw from the historic monthly joint frequency distribution of wind speed and direction. This draw is independent of ERC, and each day's draw is independent of the others.

A wildfire in FSim grows until it is either contained or self-extinguishes. FSim includes a suppression module based on a containment probability model (Finney et al. 2009) that relates the likelihood of fire containment on a given day to current and previous fire growth. Containment success is simulated stochastically based on comparison of a random draw with the modeled containment success probability. Self-extinguishment occurs when ERC remains below the 80th percentile value for several days in a row.

FSim produces an estimate of the circa 2008 burn probability, not estimates of burn probability for future fire seasons. In FSim, the fire modeling landscape (LCP – for landscape) remains unchanged between fire simulations and fire seasons; there is no attempt to simulate how simulated fires may affect future fire growth. FSim is parameterized and calibrated based on past weather and fire occurrence, typically going back about 20 years. However, the last decade has been dryer than the previous decade, therefore going back 20 years for fire history may undervalue the intensity and probability compared to what is currently being experienced. Research efforts are now underway to simulate fire likelihood under a changing climate with FSim, but those methods are not yet available for use on this analysis. FSim is designed primarily to illustrate how fire likelihood is distributed spatially across a landscape in relation to ignition density and fire growth potential. The absolute level of likelihood is assumed to be roughly equal to that indicated by past fire occurrence. If that is not the case, FSim's results could under- or over-estimate actual BP, and based on the recent shift in fire behavior from historical patterns, it is possible that in this case it is under-estimating the actual BP.

A.1.2 FlamMap5

Although FSim has the capability of modeling fire intensity, early in our process we decided that FSim's fire intensity results under-represent low-probability, high-intensity events. Therefore, the FSim simulations were used solely to estimate burn probability; potential fire intensity and the propensity for crown fire under severe conditions was estimated with FlamMap5 (Finney 2006).

FlamMap5 is a spatial fire behavior model that computes potential fire behavior characteristics such as rate of spread, flame length, and fireline intensity over the entire LCP with constant weather and fuel moisture conditions. FlamMap5 creates raster data of these fire behavior characteristics. This raster data can be viewed directly in FlamMap5 or exported for use in GIS. There is no temporal component in FlamMap5, it uses the spatial data in the LCP to calculate fire behavior characteristics, including the type of fire (surface fire, passive crown fire, or active crown fire), rate of spread, fireline intensity, and flame length. A single set of environmental conditions is used to produce a "snapshot" of potential fire behavior. In contrast to FSim, FlamMap5 calculations are made for the heading direction only, thus representing a conservative estimate of the fire behavior that could occur at the grid cell.

A.2 Model Inputs

Three broad classes of inputs are required for running FSim and FlamMap5: 1) a fire modeling landscape (LCP), which describes fuel, forest vegetation, and topography across a landscape, 2) historical weather, and 3) historical fire occurrence.

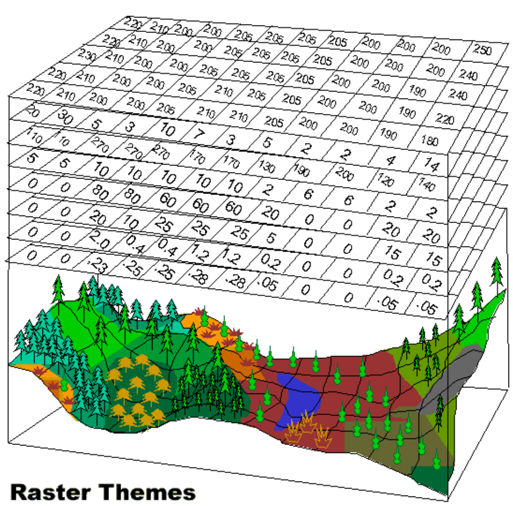
A.2.1 Fire modeling landscape

Spatial fire models need a virtual landscape on which to simulate burning. This virtual landscape—called a fire modeling landscape—is a set of gridded (raster) data layers, as shown below. On the Mokelumne LCPs, each grid cell (pixel) represents a square that is 30 meters on a side, representing approximately 0.22 acres. The Mokelumne LCPs consist of 10,248,068 grid cells representing 2,279,118 acres. This LCP size includes a buffer around the Mokelumne watershed so that FSim can simulate fires that ignite outside the watershed but burn into it.

The LCPs consist of data layers representing elevation, slope, aspect, surface fuel model, canopy cover, canopy height, crown base height, and crown bulk density (Figure A.1). To estimate first-order fire effects and tree mortality outputs, a fuel-loading model and tree list are needed.

LCPs representing two landscape conditions—current and treated—were created for this project. The current-condition LCP represents fuel and forest vegetation as it existed circa 2008; the treated-condition LCP represents fuel and forest vegetation as it might exist on the same circa 2008 LCP after implementation of fuel treatments across a designated portion of the watershed.

Figure A.1



Wildland Fuel Landscape file (LCP)

Elevation
Slope
Aspect
Surface Fuel Model
Canopy Cover
Canopy Height
Crown Base Height
Crown Bulk Density
Fuel Loading Model
Tree List

graphic from www.firemodels.org

A.2.1.1 Current-condition LCP

In the spring of 2012, "out of the box" LANDFIRE Data[1] LCP was used for the preliminary testing of the concept of using FSim and WFAT (Wildland Fire Assessment Tool) to help determine wildfire hazard in the Mokelumne Analysis. At this time it was determined that FlamMap5 would be used instead of the WFAT (though this tool shows great promise in providing spatial fire effects outputs) because WFAT required the use of two raster themes that were experimental and/or cumbersome to deal with.

[1] www.landfire.gov version 1.0.0

The results of our test runs were presented to the MACA Technical Committee and their feedback and a subsequent field trip to the project area helped identify the following calibration needs for the base LANDFIRE vegetation data:

1. Barren areas in the higher elevation were under represented.
2. Chaparral shrublands were also under represented in the area dominated by the LANDFIRE vegetation type of California Blue Oak-Foothill Pine (#2114).
3. Herbaceous - grassland were under represented in many areas below 4,000 feet elevation.
4. Agricultural areas below 4,000 feet elevation also seemed under represented.
5. LANDFIRE vegetation type Red Fir Forest and Woodland (#2032) seemed over represented in areas above 4,000 feet that appeared to be mountain shrublands.

An expert opinion crosswalk between CALVEG[2] and LANDFIRE Existing Vegetation Type (EVT) was developed by USFS Fuels Planner - Phil Bowden & USFS Fire Ecologist - Neil Sugihara to make the above listed adjustments to the LANDFIRE Vegetation data files. Using GIS, the initial CALVEG adjusted LANDFIRE vegetation Type (**EVT**), Cover (**EVC**), and Height (**EVH**) raster files were created by Phil Bowden. These raster files were then used in the 0.12 version of the LFTFC[3] (LANDFIRE Total Fuel Change) Tool for ArcGIS 10 to make the required calibrated LCP.

LFTFC uses rule sets for all EVT, EVH, EVC, and Fuels Disturbance Code (FDIST) combinations to determine Fuel Model assignment. Fuel canopy attributes are calculated by standard Forest Vegetation Simulator/ Fire Fuels Extension[4] (FVS/FFE) forest growth simulation model runs by FDIST, EVT, EVH, and EVC combinations. The LFTFC tool performs all calculations at the pixel level, not the stand level.

At a later date, GIS Specialist Allison Mead – National Forests in Florida – used the Model Builder in ArcMap to make the CALVEG adjusted LANDFIRE EVT, EVC, and EVH in a systematic way covering a slightly larger area than the initial raster files that Phil Bowden made. These final calibration raster files were completed for both LANDFIRE versions 1.1.0 & 1.0.5. Because version 1.1.0 has some imbedded vegetation changes (2001 -2008), the calibrated LANDFIRE version 1.0.5 (circa 2001) was used to bring both baseline and treatment scenario LCPs forward to the baseline year of 2008 using the LFTFC tool. This method avoided modeling a disturbance on vegetation data that already had been changed. The baseline scenario used the 2001- 2008 LANDFIRE Fuel Disturbance grid (FDIST) with the addition of a custom FDIST code applied only to Working Forest treatments.

The project-specific calibrated LANDFIRE version 1.1.0 (circa 2008) was used by other modeling specialists that needed 2008 baseline vegetation information as part of our project, but was not used for fire modeling.

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[2] CALVEG Info: http://www.fs.fed.us/r5/rsl/projects/mapping/accuracy.shtml

[3] LFTFC & WFAT Info: http://www.frames.gov/partner-sites/niftt/tools/niftt-current-resources/

[4] FVS/FFE Info: http://www.fs.fed.us/fmsc/fvs/

Note: The LFTFC can also help in reducing seam lines at LANDFIRE zone boundaries. This is done by making constant fuel model rule sets at the project level across LANDFIRE mapping zones. For the Mokelumne landscape there are two LANDFIRE zones involved.

A.2.1.2 Treated-condition LCP

The 0.12 version of the LFTFC tool was used again to create the necessary raster files to make the treatment scenario landscape files (LCP). The LFTFC tool uses a Fuels Disturbance (FDIST) raster file to simulate disturbance such as wildland fire and vegetation treatments. Also, LFTFC can change the four different fuel canopy attributes by a percentage. This level of detail for modeled vegetation treatments seems to be appropriate for this landscape scale analysis but would be of questionable value at the project scale.

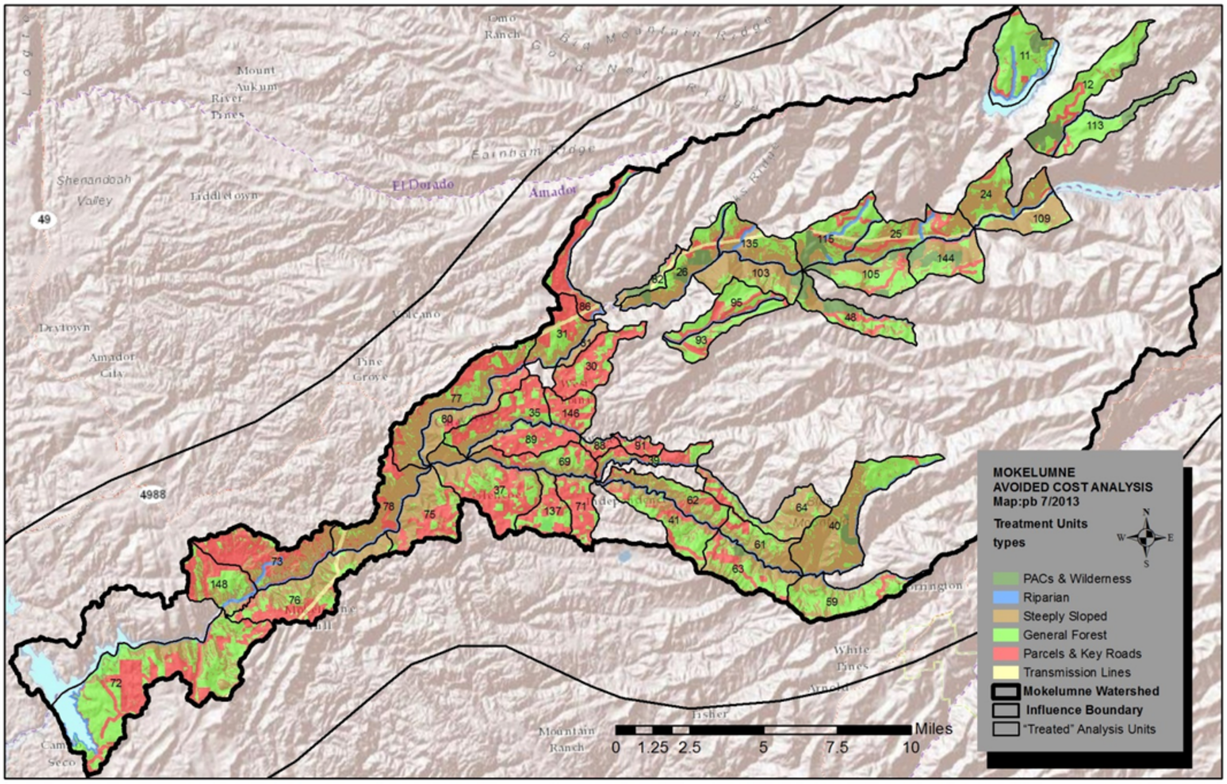
The matrix below (Table A.1) was used by the treatment team to apply FDIST codes and fuel canopy change factors to modeled treatment areas (Map A.1) selected by this same group (see chapter 2).

Table A.1 LFTFC below denotes calculated by the LFTFC tool

Land Type	*FDIST*	*Canopy Code*	*CC factor*	*CH factor*	*CBH factor*	*CBD factor*
Wilderness-Roadless	**112**	**1**	**LFTFC**	**LFTFC**	**LFTFC**	**LFTFC**
CSOPACs	**112**	**1**	**LFTFC**	**LFTFC**	**LFTFC**	**LFTFC**
Riparian	**312**	**1**	**LFTFC**	**LFTFC**	**LFTFC**	**LFTFC**
Steeply Sloped	**322**	**1**	**LFTFC**	**LFTFC**	**LFTFC**	**LFTFC**
General Forest	**322**	**2**	**0.8**	**1.2**	**LFTFC**	**LFTFC**
Key Roads	**322**	**3**	**0.7**	**1.4**	**LFTFC**	**LFTFC**
Parcels with Structures	**322**	**3**	**0.7**	**1.4**	**LFTFC**	**LFTFC**
Transmission Lines	**322**	**4**	**0.7**	**0.6**	**LFTFC**	**LFTFC**

The FDIST is the input layer that simulates recent disturbances and is required when using the LFTFC tool. The FDIST is available from the LANDFIRE Data Distribution Site for disturbances prior to 2009. Most of the model parameters for FSim and Flamamp5 were held constant from the baseline scenario to the treatment scenario; the only thing that changed was the LCP fuel and canopy characteristics shown in the matrix and map.

Map A.1



A.2.2 Historical weather

All weather and related Fire Danger indexes data were obtained from the National Fire Danger Rating System (NFDRS) for the Mount Elizabeth (#43605) Remote Automated Weather Stations (RAWS) (http://raws.fam.nwcg.gov/). This RAWS is located in southern part of the Mokelumne landscape. Other RAWS were considered, including Beaver (#42601) and Mount Zion (#42701). The Mount Elizabeth has, in general, higher wind speeds during the fire season, wind direction for the 10:00 AM – 8:00 PM time period, and has a good mix for wind directions from the two other stations considered. The reliable weather history and the fact the FPA also uses Mount Elizabeth data were factors in station selection. Using the Mount Elizabeth data in the program FireFamilyPlus (http://www.firemodels.org/index.php/national-systems/firefamilyplus), the seasonal trend of ERC and the joint monthly distributions of wind speed and direction were determined. This information is used by FSim to produce artificial weather streams with the same statistical properties as the weather records inputted into FireFamilyPlus. These weather streams enable generation of the thousands of artificial ERC trends for the fire season in FSim. This RAWS is also used by FSim to randomly and independently draw a wind speed and direction for each day of a simulation.

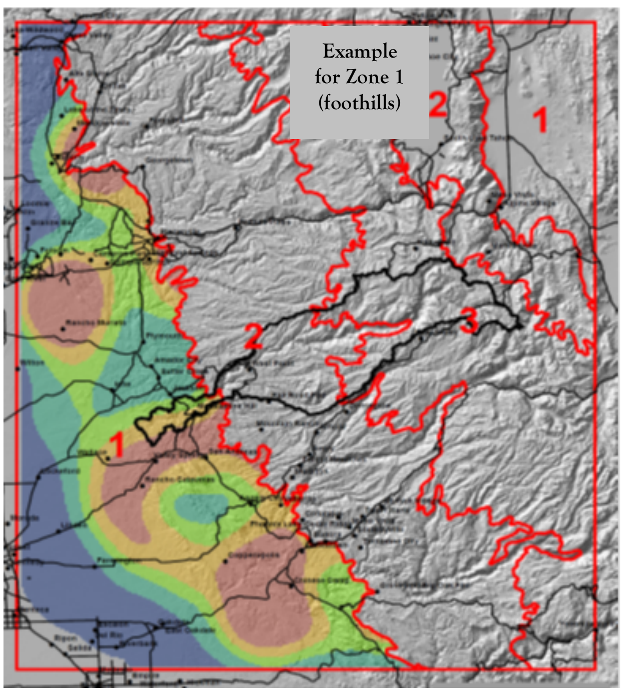
A.2.3 Historical fire occurrence

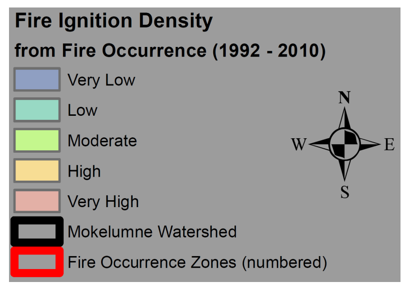
Historical wildfire occurrence data is needed to parameterize and calibrate FSim. The data used in this modeling was the spatial database of wildfires in the United States, 1992-2010 (Short 2013), developed for FPA. This dataset includes fire occurrence from all jurisdictions within the local area. From this dataset, spatial and temporal analyses were conducted to generate inputs to FSim. The historical wildfire occurrence data was gathered from an area two-times the size of the zones modeled in FSim and that data was then proportioned to zone sizes. This was an effort to get a larger sample size of fire occurrence data.

A.2.3.1 Spatial

Since fires do not start uniformity over a landscape, an ignition density grid (Map A.2) was developed to enable FSim to locate simulated fire ignition proportionally to where they happened in the past (1992-2010). FSim models the probability of large fires, so the purpose for using historic fire locations was because the fires that escape the initial fire suppression response are likely to become multiday events.

Map A.2



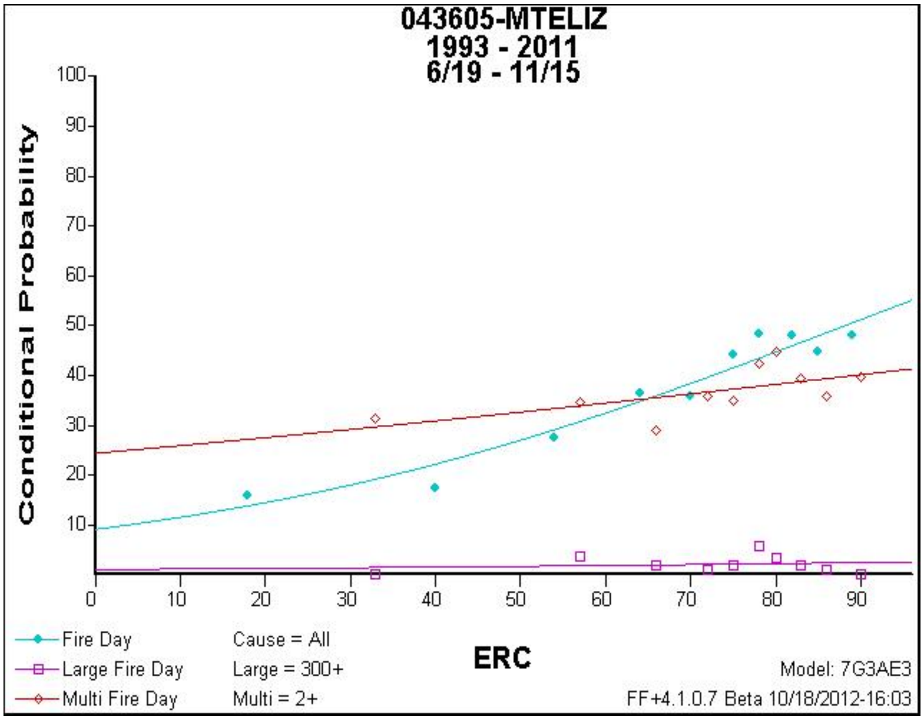


Ignition density grids were developed for three zones: 1) Low Elevation 2) Mid Elevation and 3) High Elevation. The zone boundaries were based on the National Hierarchical Framework of Ecological Units.

A.2.3.2 Temporal

An analysis of the probability of a large fire starting on a given day in a season was accomplished by using the program FireFamilyPlus, which associates the historic wildfire occurrence data with the weather and fuel moisture from the RAWS (Figure A.2). As discussed earlier, FSim is intended to simulate the large spreading fires and as such FSim constrains the growth of simulated fires to days when the ERC is $\geq$ the 80th percentile recorded at the RAWS.

Figure A.2



Conditional large fire probabilities (as shown on the graph to the left) were developed for same three zones as listed on the previous page: 1) Low Elevation 2) Mid Elevation and 3) High Elevation.

A.3 Fire modeling specifics

A.3.1 FlamMap5

Once the baseline fire modeling landscape (LCP) was completed, an initial FlamMap5 run was performed with the parameters listed in Table A.2. Early testing of sediment production modeling was done by using these initial flame length outputs in addition to the vegetation data to determine modeled soil burn severity. Subsequent concerns and discussions by MACA Technical Committee members about the high proportion of landscape being classified as high severity compared to recently burned areas in the Sierra Nevada led to multiple FlamMap5 simulations to try to calibrate closer to recent historic soil burn severity. The final calibration used the parameters listed in yellow below and had better proportions of low, moderate, and high severity as related to historic. Fuel Moisture used in the FlamMap 5 simulations are the average values that correlates to the 80th percentile ERC data from Mount Elizabeth RAWS (March 20 – November 1, 2002 – 2012). All simulated wind directions were uphill. Final Calibration wind speed is the 10 minute average at 20' under 80th percentile ERC.

Table A.2

		Crown Fire	Fuel Moisture %					
FlamMap5 Run	20' Wind	Model	1hr	10hr	100hr	Herbaceous	Woody	Foliar
Initial	15 MPH	Scott	4	5	6	45	86	100
Final Calibration	12 MPH	Finney	4	5	6	45	86	100

A.3.2 FSim

All FSim Simulations were done by zone (1 Low Elevation, 2 Mid Elevation, and 3 High Elevation). Each zone was modeled separately and had a unique set of historic wildfire occurrence data, along with an ignition density grid that allowed simulated fires to start only in one zone but were able to spread anywhere on the common LCP. This zone methodology helped to account for differences in the seasonality, frequency, and the suppression response of wildfire due to differences in elevation and vegetation type. A total of 33 calibration FSim simulations were completed for the MACA. Calibrations outputs for "large fires" (>300 acres) were compared to the historic wildfire occurrence data. Statistics compared were the mean annual number of fires, mean annual large fire area burned, and the mean large fire size. To speed up the calibration process, FSim calibrations were done using 270 meter resolution with 20,000 simulated seasons; these simulations took approximately 20 minutes per zone to run. Based on the calibration runs, adjustments were made in FSim to some parameters, such as the rate of fire spread to find a reasonable match to the historic large fire occurrence statistics. Once a reasonable match was found, a final FSim simulation was done for each zone using 90-meter resolution for 40,000 simulated seasons. Final simulations took approximately 6 hours per zone to run. The final 90-meter raster grid of Burn Probability (BP) results from each of the 3 zones added together in GIS to make one composite 90-meter BP raster grid. All other outputs produced by FSim, including the ESRI shapefiles containing the final perimeter of each simulated fire, were retained for possible analysis.

A.3.2.1 Statistical tests of final FSim outputs

We used the Statistical Analysis System (SAS) to statistically compare the distributions of fire size and seasonality of fires from the historic data (FPA) to the FSim output data by zone.

A.3.2.2 Fire Season distributions

There were not any statistical differences between mean Julian start dates for FPA vs. simulated fires in zones 2 and 3 (two sample t-test, P-values = 0.88 and 0.16 for zones 2 and 3 respectively, mean start dates 234 vs. 235 and 225 vs. 234 for FPA vs. simulated fires in zones 2 and 3, respectively). Start dates for FPA vs. simulated fires in zone 1 were statistically different (two sample t-test, P-value <0.001). However, the differences in mean start dates for zone 1 may have been an artifact of the data and may not be of practical significance when considering the distribution of start dates as a whole. The difference in mean start dates (212 vs. 230, FPA and simulated fires, respectively) is reflected by additional simulated fires in the latter half of the season as evidenced by a difference in the mode of the distributions of only two days (224 vs. 222, FPA and simulated fires, respectively). In addition, the latest zone 1 FPA fire start date was five weeks earlier than FPA fires in either zone 2 or 3 (294 for zone 1 vs. 329 for zones 2 and 3). In reality, there is not any practical reason that the fire season in zone 1 would end five weeks earlier than in either zone 2 or 3.

A.3.2.3 Fire Size

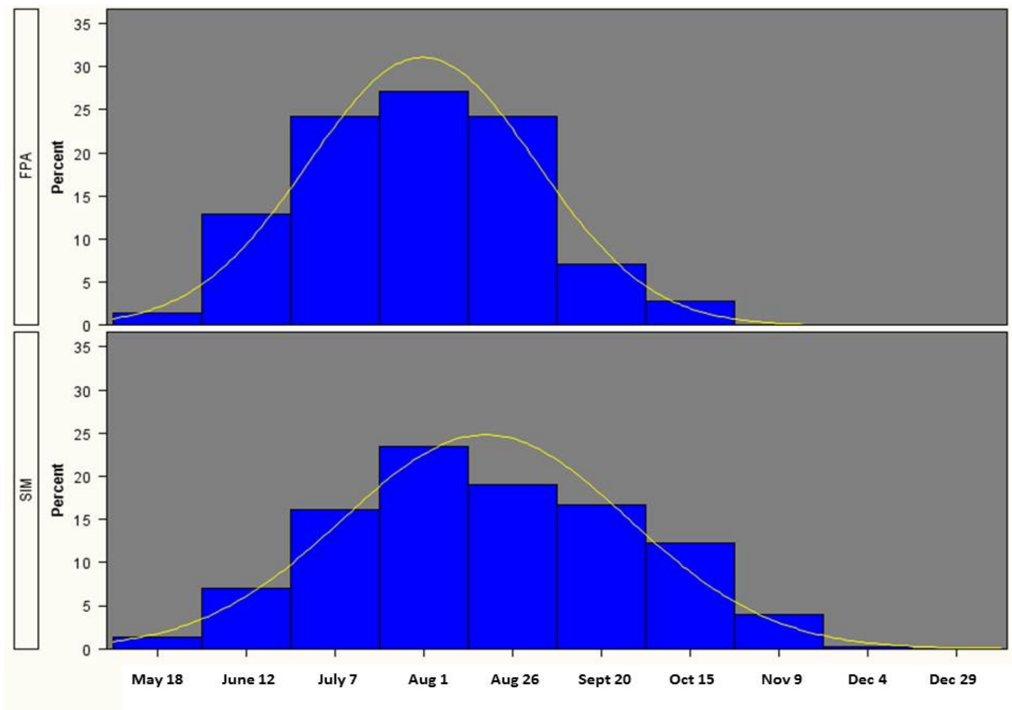
The distributions of fire sizes were similar for FPA and simulated fires across all zones, with the number of fires being inversely proportional to fire size (i.e. the largest number of fires fell in the smallest size class and number of fires decreased as fire size increased). However, the larger fire classes were fully populated for simulated fires but not for FPA fires, primarily due to the much larger number of simulated fires (70 vs. 24167, 39 vs. 28975, and 31 vs. 24453 for FPA vs. simulated fires in zones 1, 2, and 3, respectively). Graphical comparisons of these distributions are on the following three pages (Figure A.3).

Figure A.3

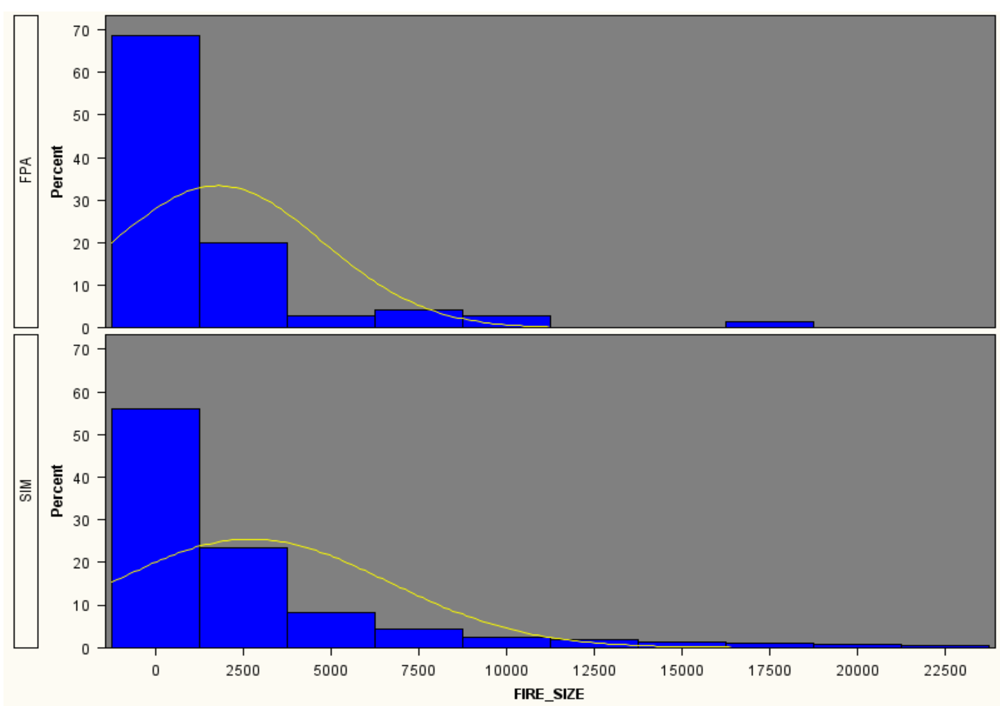
Zone 1

(Low Elevation)

Percent of fires by date



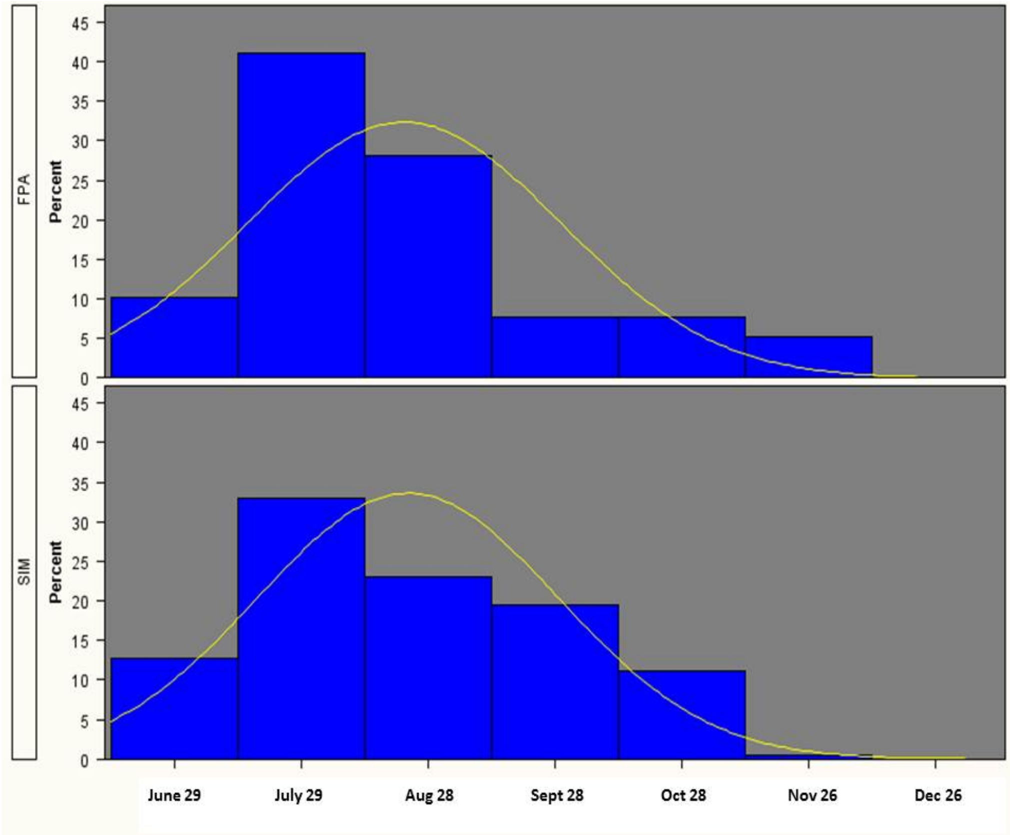
Perecent of fires by acres



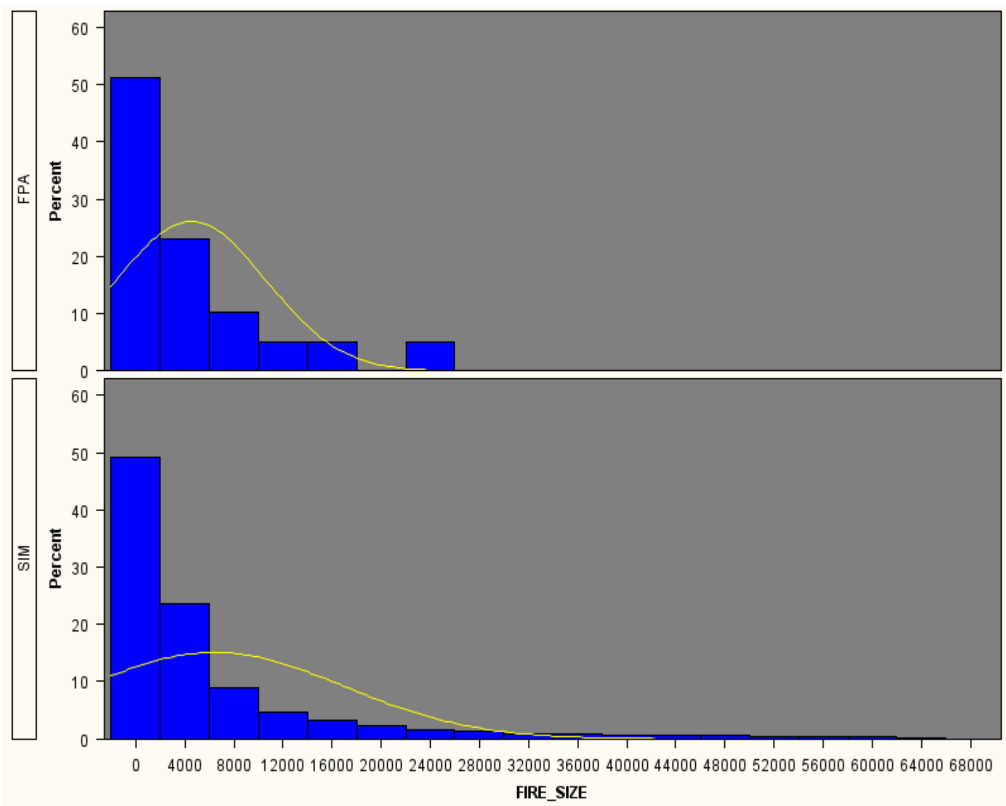
Zone 2

(Mid Elevation)

Percent of fires by date



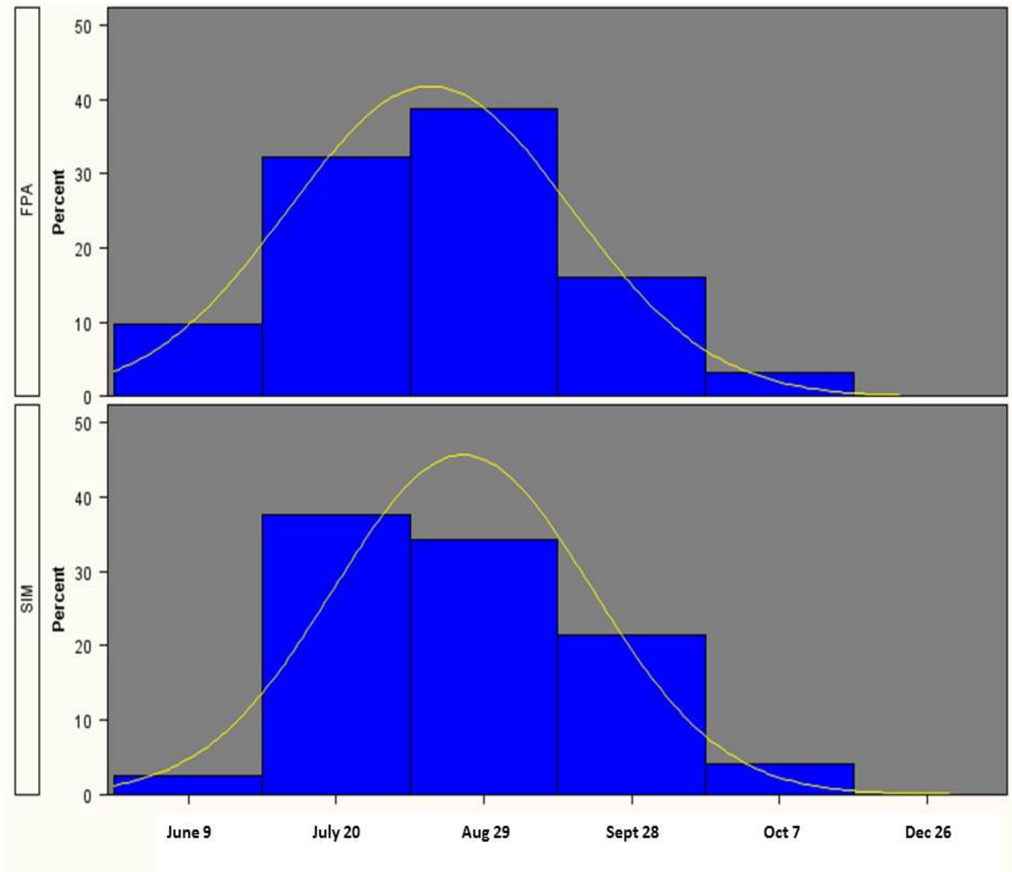
Perecent of fires by acres



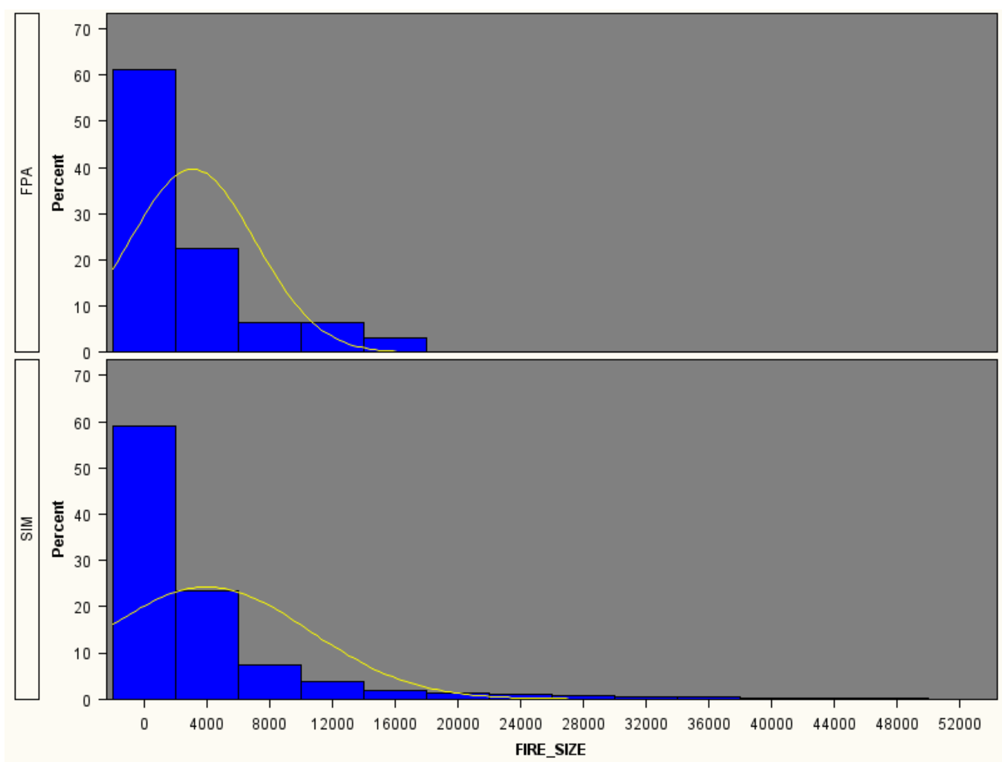
<u>Zone 3</u>

(High Elevation)

Percent of fires by date

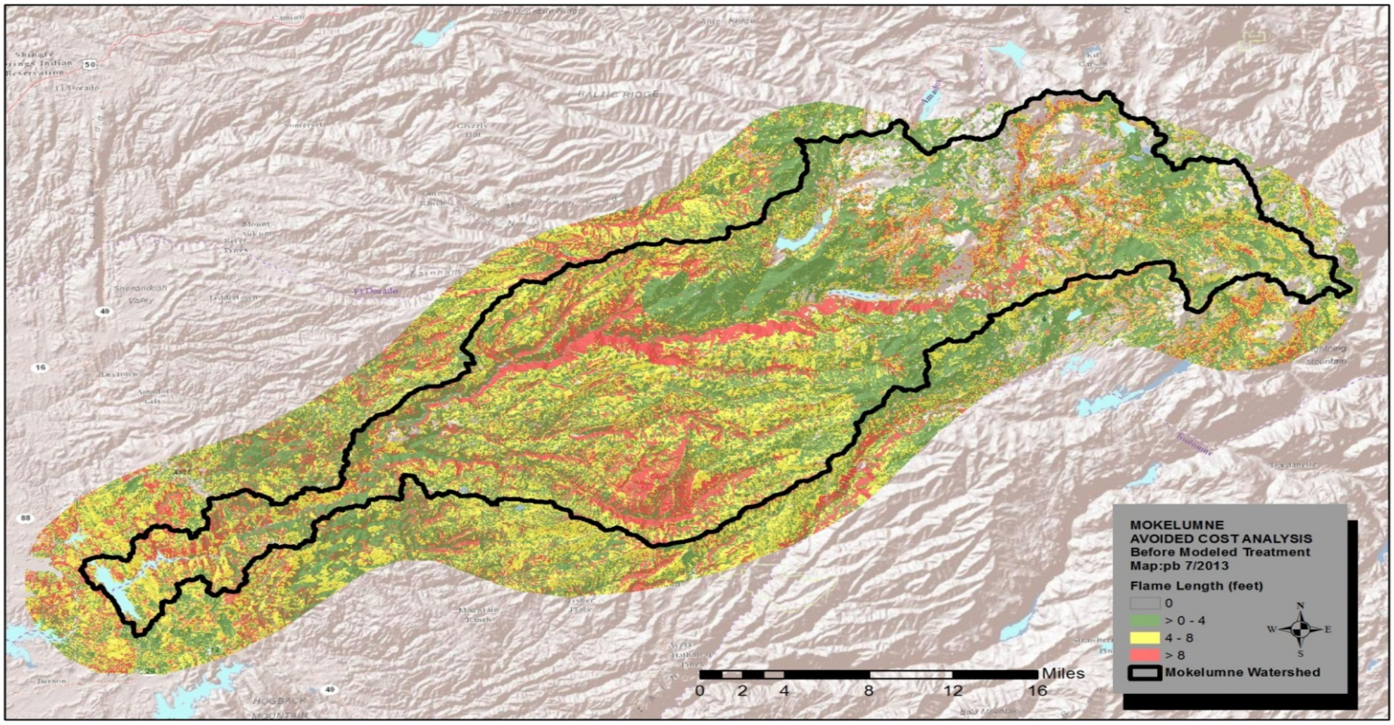


Perecent of fires by acres

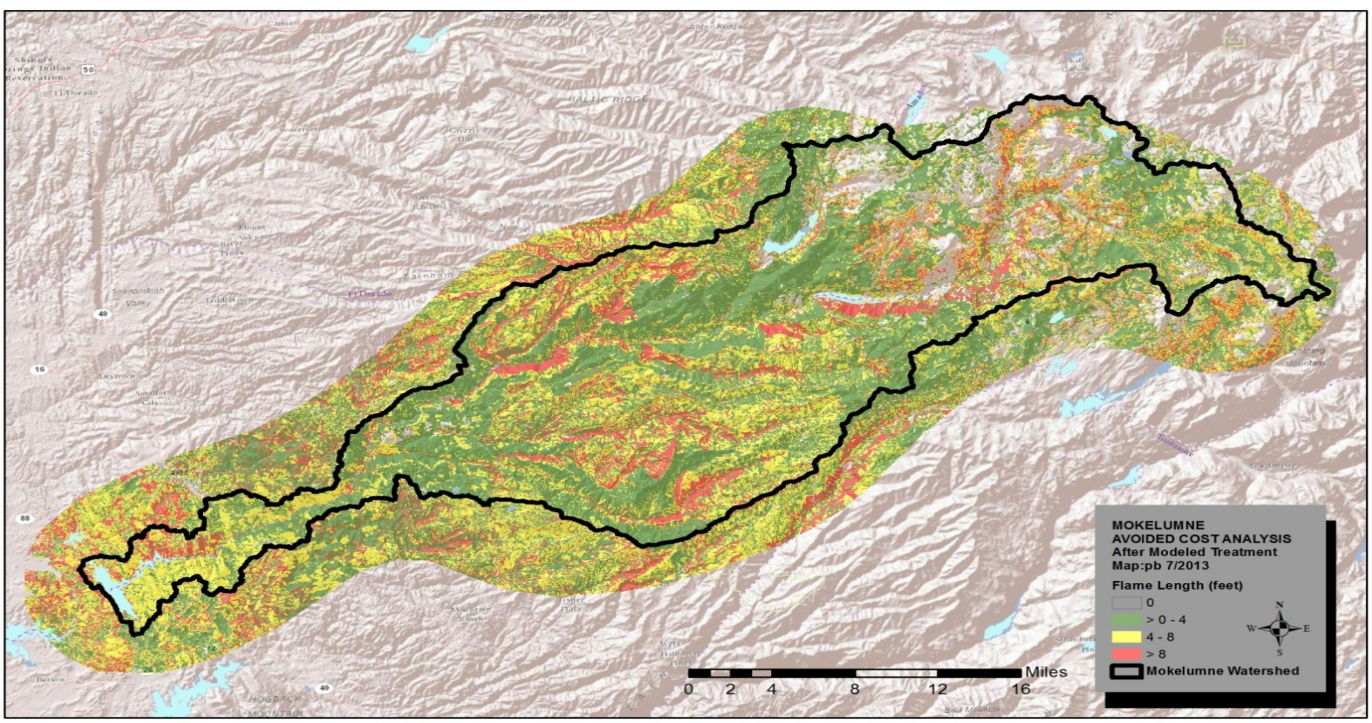


A.4 Results

Map A.3 Final FlamMap5 results – flame lengths: pretreatment



Map A.4 Final FlamMap5 results – flame lengths: posttreatment



Since wildfire hazard can be quantified as the likelihood of experiencing a wildfire and the intensity, or severity, of a wildfire if one occurs, map outputs are:

- *Intensity* - FlamMap5 Flame Length
- *Likelihood* - FSim Burn Probability for both the before & after treatment scenarios.

Table A.3 is one way to think about rating hazard in a relative way; this could be a possible way of prioritizing areas of concern if the consequences to values are equal.

Table A.3

	Likelihood		
Intensity	**Low Probability**	**Moderate Probability**	**High Probability**
Low Flame Length	Low, Low	low, Moderate	Low, High
Moderate Flame Length	Moderate, Low	Moderate, Low	Moderate, High
High Flame Length	High, Low	High, Moderate	High, High

Many interim maps that spatially combined burn probability and flame length were developed in order to map the relative wildfire hazard to help inform the selection of the hypothetical treatment locations. This fire modeling did not link this hazard to consequences in monetary values in the Mokelumne watershed; this modeling was done to provide fire hazard metrics only.

The outputs of annualized large fire acres can be calculated via multiplying the total of the burn probability for all the grid cells by the area of each cell in acres, located in table A.4. This table summarizes the annualized large fire acres for the before & after treatment scenarios within the Mokelumne watershed and also displays the possible associated fire suppression costs by fire size classes. To develop the annualized figures, the total burn area for all 40,000 fire seasons were added together and then divided by 40,000 to get totals per year across the full 40,000 season timeline.

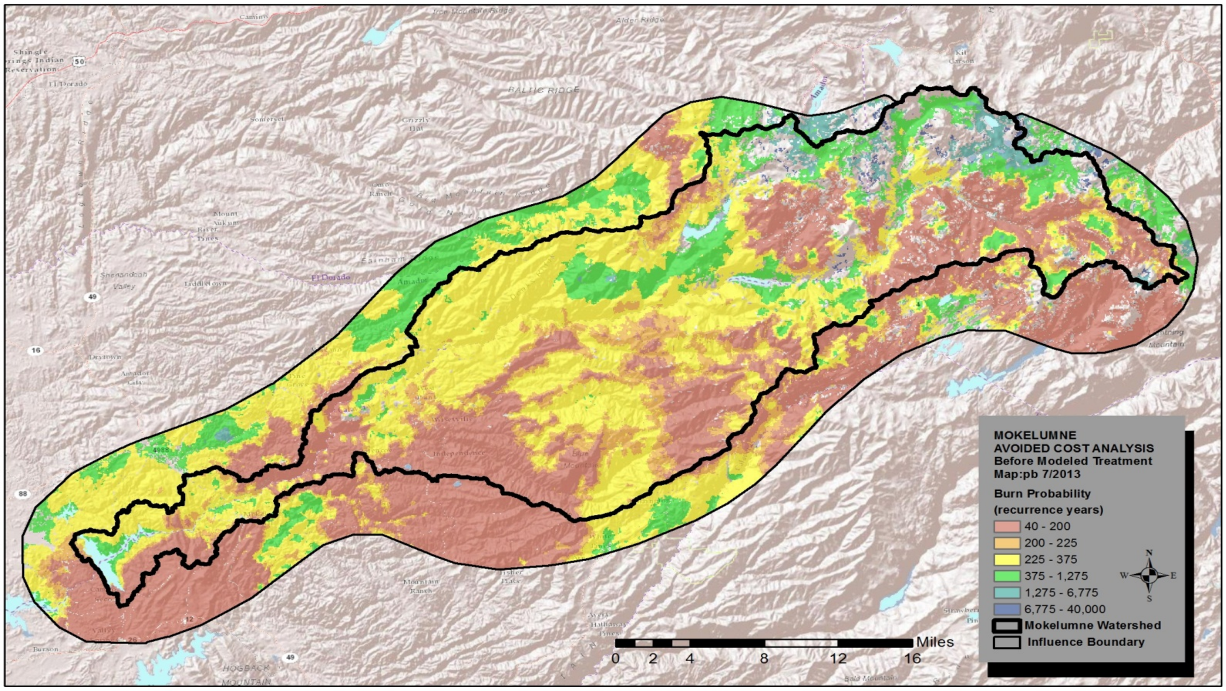
Table A.4

	Annualized Acres	Class E size	Class F size	Class G size
Cost per Acre		$1,616.00	$690.00	$1,358.00
After Treatment	1213	$1,960,208.00	$836,970.00	$1,647,254.00
Before Treatment	1480	$2,391,680.00	$1,021,200.00	$2,009,840.00
Change	-267	-$431,472.00	-$184,230.00	-$362,586.00

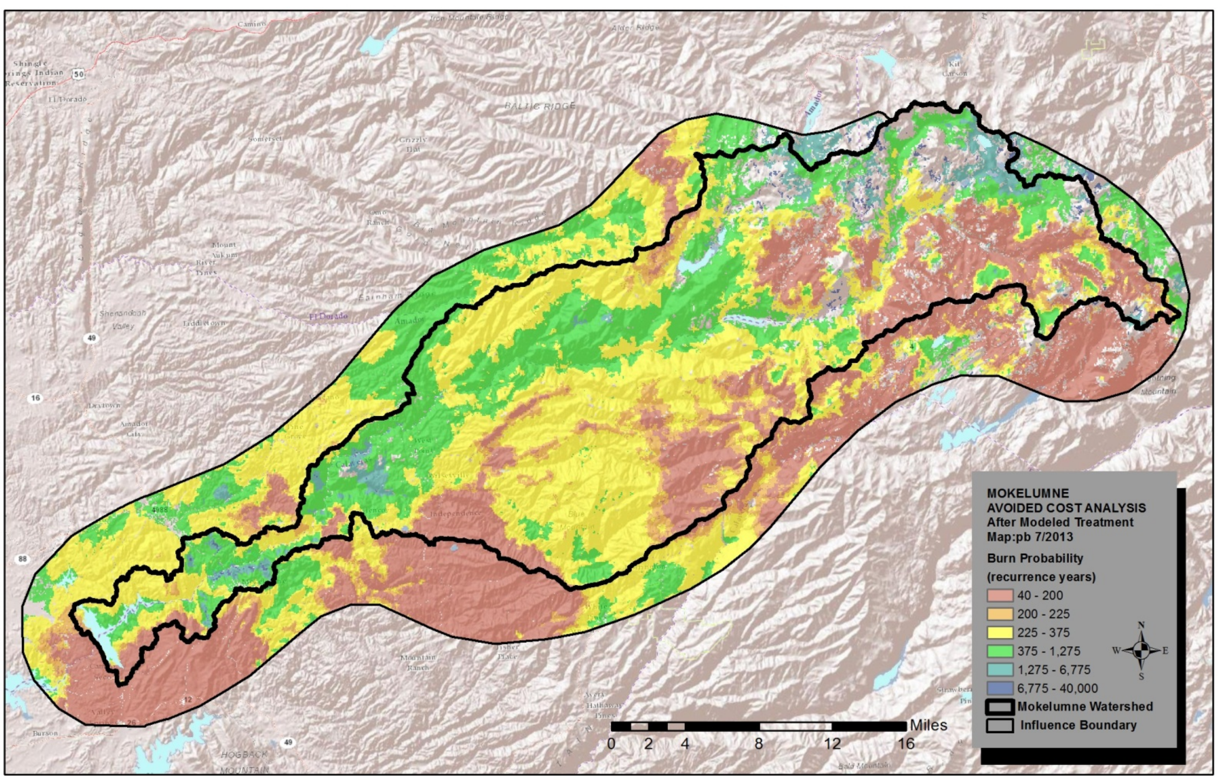
Fire Costs are actual fire costs for the Eldorado National Forest (2001 -2010) adjusted for inflation.

Size of wildfire: Class E - 300 acres or more, but less than 1,000 acres; Class F - 1,000 acres or more, but less than 5,000 acres; Class G - 5,000 acres or more.

Map A.5 Final FSim results – burn probability (in recurrent years): pretreatment



Map A.6 Final FSim results – burn probability (in recurrent years): posttreatment



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Appendix B: Insects, Diseases, and Abiotic Factors

B.1 Current Condition

The desired state of forest health, in relation to insects and diseases, is the condition in which these agents do not threaten ecosystem structure and function and/or management goals and objectives. Many of the forest types in the Mokelumne watershed are showing symptoms of forest health decline. In many areas, fire exclusion, grazing, logging activities, or no management, have combined with environmental and ecosystem changes to create overly dense stands, a loss of age diversity, and an altered mix of vegetation. This alteration of conditions has resulted in an increase in susceptibility to insects, pathogens and weather-induced stresses. Bark and engraver beetles, root diseases, mistletoes and an introduced fungus which causes white pine blister rust are important forest insects and diseases in the Mokelumne watershed.

Historically, the most significant widespread effect on vegetation has been conifer mortality associated with bark beetles and severe moisture stress. Conifer mortality tends to increase when annual precipitation is less than about 80% of normal (S. Smith, unpublished data). Trees stressed by inadequate moisture levels have their normal defense systems weakened to the point that they are highly susceptible to attack by bark, engraver and woodboring beetles. The bark and engraver beetles operating in the Mokelumne watershed are native and have coevolved with their host species. These beetles are fairly host specific which assists in determining the cause of tree mortality. Red and white fir mortality is associated with attacks by the fir engraver beetle (*Scolytus ventralis*). Mountain pine beetle (*Dendroctonus ponderosae*) attacks sugar pine, western white pine, whitebark pine, lodgepole and ponderosa pine. Western pine beetle (*Dendroctonus brevicomis*) attacks ponderosa pine and Jeffrey pine beetle (*Dendroctonus jeffreyi*) attacks Jeffrey pine.

Each of the past seven years, between 1,000 – 7,000+ acres in the Mokelumne watershed have had some level of tree mortality caused by bark and engraver beetles[1] (Table B.1 and Figure B.1). The highest number of acres with mortality has been attributed to fir engraver beetle, primarily in white fir, and mountain pine beetle in lodgepole pine. Effects resulting from bark beetle-caused tree mortality can include openings that vary in size, fewer trees/acre, reduced canopy closure, increase in standing dead and down woody material, increase in fuel load, increase in decomposition and nutrient cycling, increase/decrease in species diversity, and changes in forest structure and species composition. The importance or significance of these effects depends on their severity and extent, and ultimately how they affect ecosystem structure and function and specific management goals and objectives.

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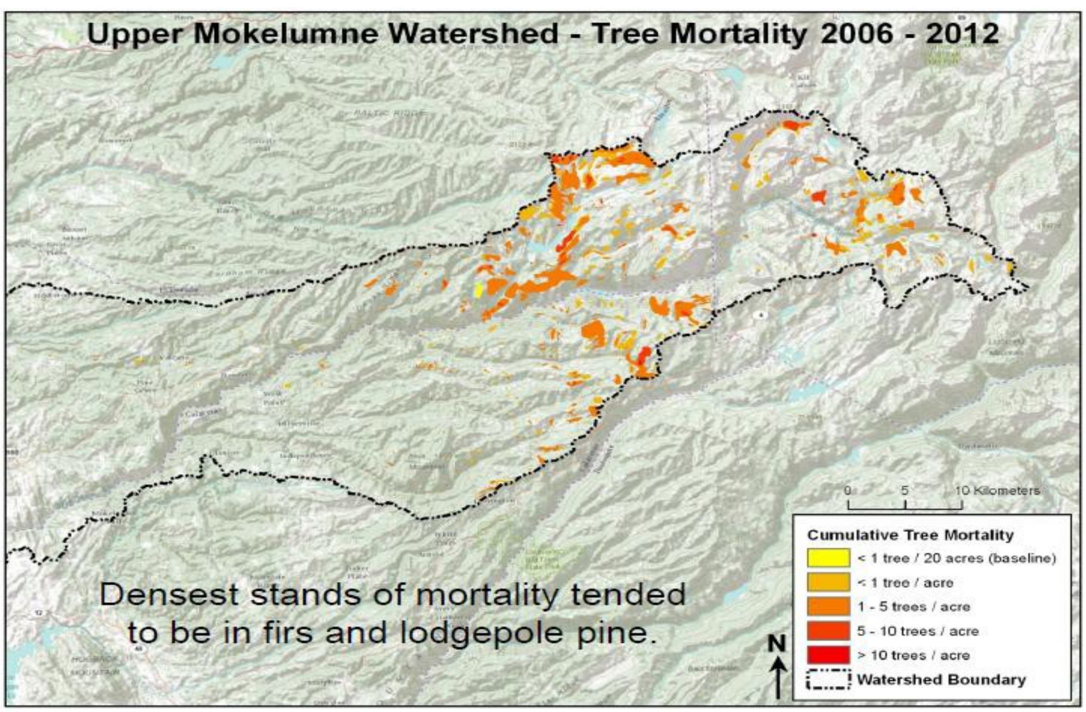
[1] http://www.fs.usda.gov/detail/r5/forest-grasslandhealth/?cid=fsbdev3_046696
http://caforestpestcouncil.org/meetings-reports/

Table B.1: Number of acres with tree mortality primarily caused by bark beetles in the Mokelumne watershed

Host Species	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*Totals*
Lodgepole Pine	732	2,753	231	1,874	472	1,248	1,176	*8,487*
White Fir	27		16	2,529	2,910	829	8	*6,319*
Mixed Conifer	4,893	73	228		924			*6,118*
Firs	554	502	105	434	1,843	997		*4,434*
Pines	11	3,425	15	283	32	125		*3,892*
California Red Fir	1,051		73	1,435	308	248	12	*3,127*
Ponderosa Pine	57	7	365	322	431	246	155	*1,583*
Western White Pine	3		1	268		21	90	*383*
Jeffrey Pine	125	2	45		91	8	36	*307*
Sugar Pine	6		5	13	1	52	41	*119*
Whitebark Pine	2		2	2	2		4	*13*
Totals	*7,461*	*6,762*	*1,086*	*7,160*	*7,014*	*3,775*	*1,523*	*34,781*

Source: Forest Health Protection, Aerial Detection Survey program.

Figure B.1: Cumulative tree mortality primarily caused by bark beetles in the Mokelumne



Source: Forest Health Protection, Aerial Detection Survey program.

Heterobasidion root disease (*Heterobasidion* sp.) is one of the most important conifer diseases in the Sierra Nevada and likewise in the Mokelumne watershed. This root disease, in combination with the fir engraver beetle, has contributed to high levels of white fir mortality in the watershed. In recreation areas, Heterobasidion root disease-infected trees can be extremely hazardous, causing death or injury to visitors, and damage to property when they fail. Ecologically, this root disease decays wood in the butt and roots of trees and recycles nutrients. It can create stand openings and alter forest structure, composition, and succession, thus providing enhanced diversity and improved wildlife habitat for certain species.

Dwarf mistletoes (*Arceuthobium* spp.) are considered widespread in the Sierra Nevada range and occur in the Mokelumne watershed. They can be a major cause of growth loss and a reduction in vigor, with the degree of growth reduction dependent upon the intensity of infection and the location of the mistletoe in the tree. Dwarf mistletoes can kill trees directly, but it is more common to find heavily infected trees attacked and killed by bark beetles and/or woodborers.

White pine blister rust (*Cronartium ribicola)* has been devastating to sugar pine since the disease entered northern California around 1930. Although the spread of blister rust in the Sierra Nevada range has been slow and erratic, infections have been reported over the entire range of sugar pine, except for in a few isolated areas. All age and size classes of sugar pines are highly vulnerable to the disease, which can eventually result in branch kill, whole tree mortality or infestation by mountain pine beetle. This rust has also been found on western white pine (*P. monticola*) and whitebark pine (*P. albicaulis*) in the upper reaches of the watershed.

Table B.2: Key forest health indicators and agents

Indicator	*Agents*	*Measures*	*Source*
Acres, %, or number of trees affected by native insects and diseases	bark/engraver beetles; root diseases	Number of dead trees; % infected trees	Aerial surveys; ground surveys; FHP evaluations; CAIDA; FIA data; pertinent literature and reports.
Acres, %, or number of trees affected by abiotic processes (non-fire)	Weather related; ozone		Aerial surveys; ground surveys; FHP evaluations; CAIDA; FIA data; pertinent literature and reports.
Acres, %, or number of trees affected by invasive insects and diseases	White pine blister rust	% infected trees	Aerial surveys; ground surveys; FHP evaluations; CAIDA: FIA data; pertinent literature and reports.
Acres susceptible to native insects and diseases (overall risk, % host BA loss, % total BA loss)	bark/engraver beetles *Heterobasidion* sp.	Total SDI, % host, host, QMD, drought frequency Annual temp., annual precip., soil moisture regime, host QMD, % host, host BA, total BA; annual relative humidity	NIDRM, pertinent literature and reports.

FHP: Forest Health Protection; CAIDA: California insect and disease atlas; NIDRM, National insect and disease risk map; FIA, Forest Inventory and Analysis; SDI, Stand density index; QMD, quadratic mean diameter; BA, basal area

B.2 Bark Beetles

Native bark beetles are a major cause of tree mortality in the Mokelumne watershed. When, where, and the extent to which they cause tree mortality is typically influenced by forest stand conditions and weather patterns. A dramatic increase in the number of dead trees follows one to several years of inadequate precipitation. The more severe and prolonged the drought, the greater the number of dead trees. Dense stands are particularly susceptible to bark beetle attacks due to stress caused by increased competition for limited resources. Stressed trees are suitable host material for bark beetles; their successful colonization results in increased beetle populations and higher levels of tree mortality. Bark and engraver beetle-caused mortality in pine types occurs primarily as small groups of trees, whereas fir mortality caused by the fir engraver beetle can occur as single trees scattered over several hundred acres. Successful attacks by pine bark beetles almost always result in tree mortality. Successful attacks by the fir engraver can result in top-kill, branch kill, or whole tree mortality. In general, bark beetle-caused tree mortality occurs in stands with high tree density, however during periods of protracted drought, mortality may be expected to occur in less dense stands as well.

Bark beetles spend most of their lives beneath the bark of their host and are only exposed to outside environments when they mature and disperse to find new hosts. For most conifer species, there is at least one bark beetle that is capable of killing the tree under the right conditions. Bark beetles are fairly opportunistic and usually require their hosts to be under some form of physiological stress for colonization to be successful. Some of the typical agents of stress, in addition to drought, include defoliating insects, various tree diseases, and a number of abiotic agents (air pollution, fire, wind damage, mechanical injury, etc.). Populations of bark beetles can fluctuate dramatically from year to year depending on the degree to which stress agents are operating in the forest. Available food source (i.e. the availability of stressed trees) is the ultimate regulator of bark beetle populations.

B.3 Root Diseases

Root diseases are important natural disturbance agents in the Mokelumne watershed. Root disease organisms kill host cambium, decay wood, plug water conducting tissue, or cause some combination of these effects. Tree death resulting from root disease can occur when trees die outright, when those with decayed roots are wind thrown, or when bark beetles attack weakened trees. Some root pathogens are favored by conditions associated with low host vigor, others are able to cause infection regardless of tree condition. Some are quite host specific, while others can infect multiple hosts. Susceptibility to root disease pathogens also varies with host age and/or geographic location.

Root diseases exert profound influences on forest structure, composition, function, and yield. Root diseases are important gap formers, creating openings in the forest of varied sizes, depending upon the pathogen(s) and hosts present. They also influence tree species composition by selectively killing some species while not affecting others. Stocking levels may be reduced in discrete areas or across stands depending on the distribution of inoculum and the tree species present. Species diversity may increase or decrease depending upon location. Root diseases influence structure by reducing the likelihood that some trees will achieve large sizes, or by slowing the process. Root diseases kill trees creating snags and down woody material that are important for wildlife habitat, and also create down woody material that is important for soil water holding capacity and nutrient cycling. This material can also contribute to fuels accumulation.

Heterobasidion sp. infect a wide range of woody plants. Trees suffering from root rot are markedly less able to absorb and translocate sufficient water. During periods of drought, trees with decayed roots are more likely to die, usually as a result of bark beetle attacks. Affected trees are also more vulnerable to wind throw. In true firs, the fungus causes root and butt decay more often than mortality, at least in larger trees. This may result in wind throw and increased susceptibility to engraver beetle attack. Potential impacts of the disease include increased susceptibility of infected trees to attack by bark beetles, tree mortality, and the loss of site productivity. In recreation areas root diseases can result in the depletion of vegetative cover, loss of aesthetic views, and raise great concern regarding tree failure. Heterobasidion-infected trees can be extremely hazardous, causing death or injury, and damage to property when they fail.

B.4 Mistletoes

Parasitic flowering plants commonly known as mistletoes are found in the Mokelumne watershed. Two genera of mistletoes are native: *Phoradendron* (true mistletoes) and *Arceuthobium* (dwarf mistletoes). The true mistletoes grow on both conifers and broadleaf trees; the dwarf mistletoes grow only on conifers. Although both mistletoes are damaging parasites of trees, by far the greatest timber loss in coniferous forests is attributed to dwarf mistletoes. They also cause serious damage to trees in high-value, high-use forest recreational areas.

B.5 Abiotic Agents

Drought can be a local problem when plants are growing in soil with a low moisture holding capacity, or can be more widespread when insufficient precipitation occurs. Reduced moisture availability increases the susceptibility of plants to injury and mortality caused by insects and diseases. Ozone damage is especially likely to occur in forests located near some of the passes and on the west side of the Sierra Nevada range, due to polluted air from areas with high vehicular traffic. Ozone affected trees are less vigorous and are more easily affected by diseases and bark beetles. The application of de-icing salt along roads can lead to needle tip dieback of conifers. Symptoms are usually evident within 100 feet of the road on the down slope side, although this distance may increase along drainages. Most herbicide injury is a result of improper application. Injury is usually found along roads, rights of way, fuel breaks, dwellings, or other areas where herbicides are improperly applied.

Fire can outright kill trees, cause injuries that result in eventual mortality, or can cause injured trees to be more susceptible to bark beetles and woodborers, thus also resulting in tree mortality. A fire-injured trees susceptibility to bark beetles is determined by the amount of injury and the tree's response, the time of year fire occurs, populations of bark beetles within the vicinity, and pre- and post-fire weather patterns (Gibson and Negron 2007). In addition, bark beetle-caused tree mortality may result in changes to fuels complexes and fire behavior during and following beetle outbreaks.

Severe winter storms cause tree injury in the forms of windthrow, breakage, or stem deformations from snow loading. Green slash or injured live trees can be highly attractive to engraver and bark beetles.

B.6 Invasive Diseases

The most damaging conifer rust in California, white pine blister rust (WPBR), was introduced to the west coast of North America in 1910 and continues to pose a serious threat to regeneration and management of sugar pine in California. Because of its impacts on ecosystem diversity, it is also becoming a concern in high elevation white pines. WPBR infects needles of the five-needle white pines and spreads into branches and sometimes into the main stem. WPBR can infect even the healthiest of trees. For some trees, infection only means a slowing of the growth rate; for many others, however, infection leads to a protracted death. This disease readily kills seedlings and also can result in reduced cone production, thus negatively affecting regeneration.

B.7 Interactions of Insects, Diseases, and Abiotic Agents

Frequently, more than one causal factor contributes to tree mortality, and certain sets of factors are commonly found in association with one another. Phytophagous (plant eating) insects and tree pathogens are often close associates in forests and, usually a forest stand will be influenced by a number of different diseases and insects concurrently. One organism may affect a tree and weaken it, predisposing it to attack by another, or one organism may actually introduce another organism into the host. In addition, abiotic factors frequently function as stressors, predisposing trees to mortality caused by biotic agents.

A pattern of decreasing precipitation or changes in precipitation patterns may reduce the growth & vigor of vegetation, thereby increasing the susceptibility to mortality caused by insects and diseases. There is abundant evidence that bark beetle caused tree mortality dramatically increases in the Sierra Nevada during extreme or protracted drought periods[2]. If droughts become more frequent, of greater intensity, or are more protracted in the future, high levels of bark beetle-caused tree mortality should be expected. In addition, bark beetle population success is influenced directly by temperature effects on insect development (Powell and Logan 2005). Some bark beetle species may be able to complete additional generations in a year and timing of beetle emergence and flight periods may be altered. Stand density and host species composition are also important factors in determining drought effects. Although all stands become increasingly stressed as drought persists, tree mortality is typically higher in denser stands. Those species less tolerant of drought are likely to be attacked by bark beetles first, followed by attacks to more drought tolerant species.

Most plant pathogens are strongly influenced by environmental conditions and vigor of the host (Kliejunas et al. 2009). Climate change will directly affect the pathogen, the host, and the interaction between them, resulting in disease impacts (Brasier 2005, Burdon et al. 2006). Root pathogens such as *Heterobasidion* sp. are more aggressive when hosts are stressed, so its incidence

[2] http://www.fs.usda.gov/detail/r5/forest-grasslandhealth/?cid=fsbdev3_046696
http://caforestpestcouncil.org/meetings-reports/

and spread could increase (Kliejunas et al. 2009) under future climate regimes. Mistletoes currently play a significant role in tree mortality when trees are stressed by drought and other agents. Surveys in California indicated that trees infected with dwarf mistletoe were the first to die during drought (Byler 1978). If droughts become more frequent, of greater intensity, or are more protracted in the future, mistletoes will continue to cause mortality, be a predisposing factor to attack by bark beetles, and may also expand their range (Kliejunas et al. 2009). Although stem rusts (*Cronartium* sp.) can adapt to a wide range of environmental conditions, their tolerances are unknown. Under changing climates, the incidence of rusts will be determined chiefly by host distribution. Typically, rusts increase in intensity and distribution in "wave years" during which the weather is especially favorable for sporulation, dispersal, and infection. As climate changes, the frequency of such waves years is expected to change (Kliejunas et al. 2009).

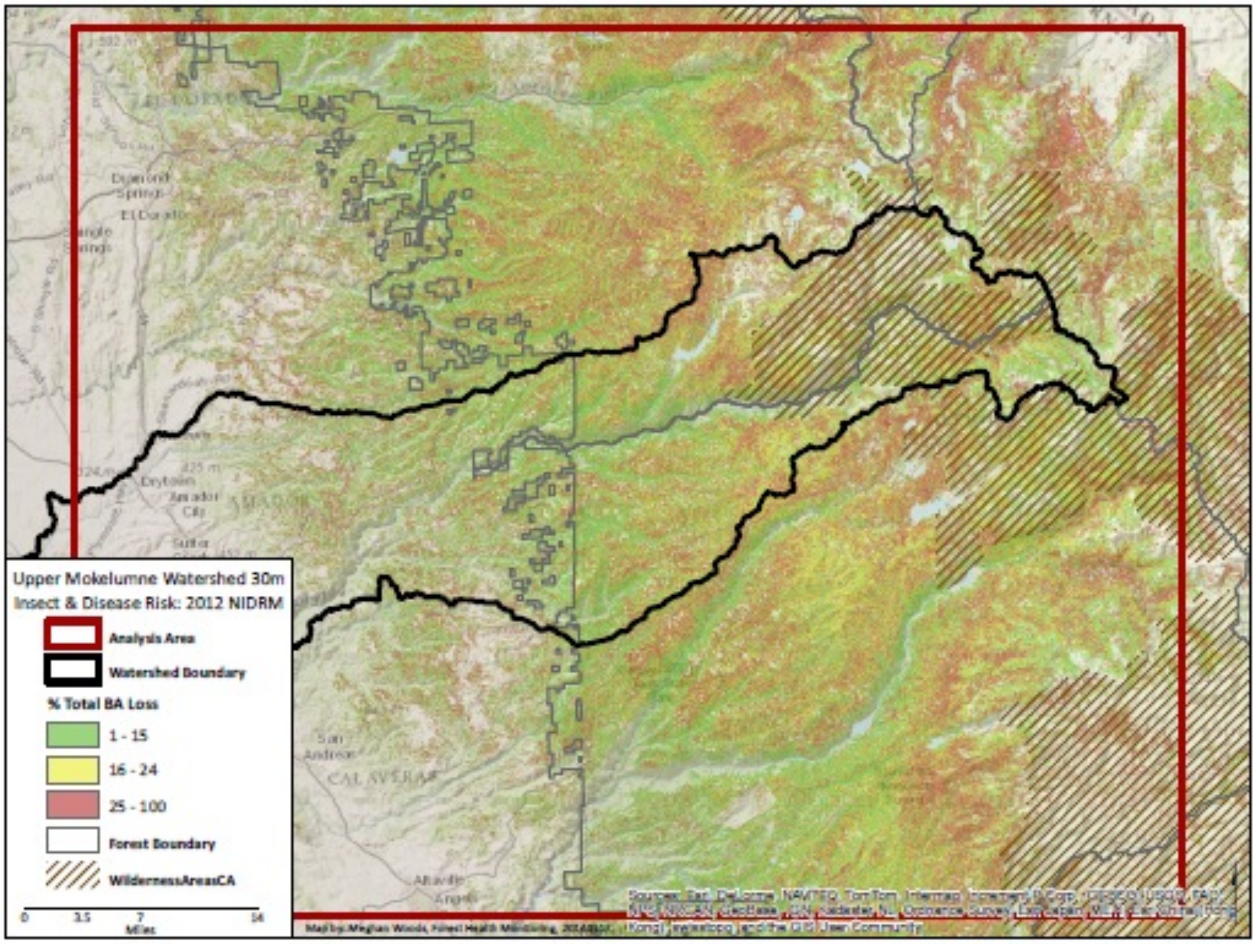
Interactions between bark beetles and fire are complex. In the long run, reintroducing fire to fire-adapted forest ecosystems will favor species and plant communities that are better adapted to these ecosystems. In the short term fire can damage residual trees to the extent that they become more susceptible to bark beetle attacks and in some cases can lead to increased bark beetle activity for one to two seasons following the fire. Areas that have already experienced bark beetle outbreaks may have altered fuel loads (and hence, potential for changes to subsequent fire behavior) for many years afterward. The specific local effects depend on a variety of factors including the number of dead trees, stand structure and species composition, aspect, and time since outbreak (Hicke et al. 2012).

B.8 Susceptibility to Future Tree Mortality caused by Insects and Diseases

Susceptibility of forests in the Mokelumne watershed to future tree mortality caused by insects and diseases was assessed nationally in 2012 resulting in the National Insect and Disease Risk Map (NIDRM)[3]. The 2012 NIDRM was driven by several models used to predict how individual tree species would react to various mortality agents. The models were developed using the interactions of predicted agent behavior and known forest parameters. The most widely used forest parameters for the NIDRM were stand basal area, stand density index, and quadratic mean tree diameter. Risk of mortality is defined as "the expectation that 25% or more of the standing live volume greater than 1" diameter at breast height will die over the next 15 years. Output for the national risk map was generated at 30m resolution. In the Mokelumne analysis area (area within the red triangle box in Figure B.2) 1,355 hectares were determined to be susceptible to high levels ($\geq$25% of the standing volume) of insect and disease-caused mortality over the next 15 years based on the 2012 NIDRM (Figure B.2). Within the watershed boundary area (within the black outlined polygon in Figure B.2) 254 hectares are susceptible to high levels of tree mortality. A 30m version of the risk map, utilizing the same models and methodology as the 240m map, will be available for future consideration.

[3] http://www.fs.fed.us/foresthealth/technology/nidrm.shtml

Figure B.2: Mokelumne watershed percent total basal area loss over the next 15 years due primarily to bark beetles



B.9 Issues and Opportunities

Acres determined to be susceptible to mortality should be surveyed for opportunities for treatment, primarily thinning to reduce stand density, if they occur where higher levels of mortality will affect the ability to meet land management objectives and goals. In general, higher levels of tree mortality may be acceptable on general forest land and in remote or wilderness areas, whereas preventing tree mortality would be preferred in campgrounds, around homes, structures, utility lines, evacuation corridors, and in areas highly susceptible to wildfire. Depending on the stand structure and density, treatments designed to meet fuels treatments alone may not reduce susceptibility to bark beetle-caused mortality. An integrated approach to determining treatment areas, residual tree density, and residual species composition will allow for strategic placement of treatment areas and afford the ability to meet multiple resource objectives with one entry.

It is important to consider the current and potential future effects from several agents of change when designing treatments aimed at reducing wildfire risks. Failure to reduce forest susceptibility to insects and diseases can lead to large-scale tree mortality that may affect forest management objectives, alter fire behavior, or require additional costly fuel reduction measures. In some situations, fuel reduction thinning can actually increase the impacts from insects and diseases, by providing slash or stumps for insect or pathogen buildup. In all cases, treatments are more likely to be cost-effective and accomplish broader, long-term forest health goals when multiple agents of change are considered prior to project implementation.

The necessity of reducing wildfire risks in urban interface areas demands comprehensive design solutions, guided by the over-arching goal of improving forest health conditions.

Responding to the threats and damage from wildfire will require a variety of treatment tools to assure long-term success and to meet broader objectives of restoring and maintaining forest ecosystem health. The consideration of insects and diseases in the planning process will help assure that success.

In many cases, insect or disease management objectives can be met by modifying the fuel treatment design. Insect and disease treatment needs vary by location, tree species, and management objectives—one treatment does not fit all.

B.9.1 Bark Beetles

Situation: Bark beetles are one of the most significant agents causing conifer mortality in western forests. Typically with many "fuels" reduction projects not enough stems (either number of stems and/or size of trees) are removed to lower residual basal area to a condition that would be much less susceptible to bark beetle attack.

Options: Thinning can reduce susceptibility to bark beetles; however, it may be necessary to thin stands to lower densities than might be adequate for fuel reduction purposes alone. Residual basal area or SDI targets that are less susceptible to bark beetle attack are known (NIDRM 2012).

Situation: Pine engraver beetles breed in fresh pine debris including thinning slash. At times, frequently during droughts, these insects attack residual trees or trees in adjacent un-thinned areas.

Options: Pine engraver beetle attacks in living trees can be reduced through greater wood utilization, slash treatment, and/or by avoiding slash creation during high hazard months.

Situation: Interactions between bark beetles and fire are complex. Reintroducing fire to fire-adapted western forest ecosystems will favor species and plant communities that are better adapted to these ecosystems. However, fire can damage residual trees to the extent that they become more susceptible to bark beetle attacks and in some cases can lead to increased bark beetle activity for one to two seasons following the fire.

Options: Include Forest Health Protection personnel when determining the likely level of post-prescribed fire mortality. Deep duff layers, around trees that are important to keep alive post-fire, should be removed prior to burning.

B.9.2 Root Diseases and Stem Decays

Root diseases and stem decays are caused by various fungal pathogens that kill or decay roots or the stem of their primary hosts, often leading to tree death. Tree thinning or fire can increase disease-caused tree mortality or cause extensive stem decay, the extent of which may not be realized for many years in the future. Once root disease becomes established in a susceptible stand, tree mortality can persist for the life of the stand and into the next rotation. Continuing tree mortality can lead to large openings in the stand or even death of most trees in the stand within one to several decades.

The goal of Heterobasidion root disease management is to reduce resource losses to levels which are economically, aesthetically, and environmentally acceptable dependent upon land management goals and objectives. Impacts of Herterobasdion root disease can be reduced through detection, evaluation, prevention, and suppression. These activities must progress in a planned, timely sequence for successful reduction of impacts. In developed recreation sites, early recognition and removal of hazardous trees is critical, and will greatly improve chances of preventing future damage with minimal site deterioration. Prevention is the most desirable means of reducing losses. Any tree can fall at any time, external and internal indicator improve our ability to make some educated guesses on which trees are more susceptible to failure so the risk can be lowered, either by removing the target or removing the tree.

Situation: Heterobasidion root disease becomes established by invading stumps following cutting, then can persist and kill trees for decades.

Options: Infection can be prevented by treating freshly cut stumps with a borate compound.

Situation: Wood decay fungi can rot the wood of living trees following fire scaring, logging injury or other means.

Options: Injury can be prevented or reduced by avoiding bole injuries to residual trees when thinning or burning, favoring decay-resistant species, or removing decayed or damaged trees in subsequent thinning.

B.9.3 Dwarf Mistletoes

There are a variety of silvicultural options that can be used to control undesirable effects of dwarf mistletoe. Many of these can be incorporated when entering stands to thin or do other management activities. Infestations of dwarf mistletoe not only affect timber values but also recreation, aesthetics, fire hazard, and wildlife habitat. In addition, mistletoe brooms can be hazardous if there is a target and they break and fall on something or someone. Mistletoe-infected trees can also be more susceptible to bark beetle attacks, particularly during low water years. Since the impacts of dwarf mistletoe are, in most cases, not significant until trees are heavily infected, the key to successfully avoiding serious effects of mistletoe on tree growth and survival, as well as associated effects on stand structure, is to prevent heavy infection.

Situation: Dwarf mistletoes are parasitic plants that infect the branches and stems of many conifers. Heavy infections can reduce tree growth and lead to premature death. In addition, the brooms formed by infected trees are highly flammable. Dwarf mistletoes are difficult to eliminate from stands and complete removal may not be desirable due to the wildlife values associated with brooms.

Options: The effects from dwarf mistletoe can be reduced during thinning by favoring non-hosts or lightly infected individuals. The probability of crown fire can be reduced by removing smaller infected trees and by pruning brooms from the lower crowns of larger trees. Pruning of large brooms can also lengthen the life of individual trees.

B.9.4 Urban Interface Forest Health Treatments

Situation: Treatments to lower the wildfire, insect and disease susceptibility of stands near communities is necessary to make them defensible from wildfires and to restore and maintain long-term tree health.

Options: With proper design, projects done primarily to reduce fuels can contribute to broader objectives. Through cooperative projects we have the opportunity to reduce fuels and address insect and disease issues in an integrated manner among multiple ownerships across the landscape.

Situation: Communities value a variety of management objectives, which can have conflicting vegetation treatment designs.

Options: It may be feasible to use a variety of treatments to result in a mosaic of stand conditions to meet a variety of objectives: to restore and maintain fire-adapted trees species; to achieve a mix of stand age classes, densities and openings; and better provide for wildlife habitat, watershed protection and visual beauty.

All of these aspects should be addressed by forest management specialists on a site-specific basis.

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Appendix C: GeoWEPP Modeling – Hillslope Erosion

C.1 Abstract

Fuel reduction treatments are effective in modifying fire behavior and reducing fire severity. However, the costs associated with fuel reduction treatments often limit their spatial application. A need exists for tools and datasets that can be used by land managers to prioritize the spatial application of treatments in order to justify their costs in a time of decreasing budgets. Fuel treatments are commonly used to provide some protection to sensitive habitats and at the Wildland-Urban Interface (WUI), but they can also be undertaken to mitigate the effects of postfire erosion on water resources. Our goal is to assist land managers and decision-makers in the Mokelumne watershed by predicting the effects of fuel reduction treatments on hillslope erosion. Burn severity was modeled for the Upper Mokelumne watershed before and after fuel reduction treatments using FlamMap. GeoWEPP with Disturbed WEPP parameters was then used to predict postfire hillslope erosion both before and after treatments; runs were also carried out to model erosion from the current landcover and the treatments. After treatments (Chapter 2) were applied in the model, the mean annual reduction in first year postfire erosion rates in the treated portion of the watershed was 20 Mg/yr^{-1}ha (Megagrams per hectare per year; one Megagram = 2205 pounds) , a reduction of 62%. If the reduction in the probability of fire occurrence and the effects of treatments are considered together, then the treatments are predicted to significantly impact long-term (century scale) erosion rates by lowering "average annual" erosion rates by 19%.

C.2 Introduction

Increased fuel loads from decades of fire suppression (Agee 1993; Keane *et al.* 2002) and climate change (Flannigan *et al.* 2000; Westerling *et al.* 2006) are increasing the risks of large, high severity wildfires in Western forests and shrublands. These high severity fires in turn increase the risk of flash floods and surface erosion (Forrest and Harding 1994; Neary *et al.* 2005). Increased postfire erosion rates can severely degrade water quality and reduce reservoir storage capacity (Tiedemann *et al.* 1979; Moody and Martin 2001; Neary *et al.*, 2005). In response to these risks, the land managers responsible for protecting forestlands and watersheds, especially those that provide water to cities and towns, want to mitigate the effects of wildfire on water resources through the use of fuel reduction treatments. Fuel reduction treatments, such as thinning and prescribed burning, have been shown to be effective in modifying fire behavior and fire severity (Cochrane et al., 2012), which can reduce threats to ecosystem services. The costs associated with these treatments, however, limit their application (GAO 1999; Sampson *et al.* 2000; GAO 2007). Therefore we are seeking to quantify the benefits of fuel reduction on postfire erosion rates in the Mokelumne watershed and to assist in the spatial prioritization of fuel reduction applications.

C.3 Modeling approach

A coupling of two different models was needed to predict the effects of fuel reduction treatments on hillslope erosion in the Mokelumne watershed. The first model, FlamMap, was used to predict burn severity both before and after proposed fuel reduction treatments (Appendix A). The WEPP model then used the burn severity predictions from FlamMap to predict hillslope erosion following wildfire both before and after treatments. An added benefit of our modeling approach is that we were able to use our predictions of postfire erosion for current conditions (before treatments) to help plan where to place fuel treatments within the watershed. WEPP runs were carried out to model hillslope erosion rates in the watershed without a wildfire. Additional runs were carried out to model erosion that would result from disturbances to the forest from the application of the proposed treatments.

C.3.1 FlamMap

FlamMap is a spatial fire behavior model that uses land cover, topography, and fuel characteristics data from the LANDFIRE database, along with fuel moisture and weather data (Finney 2006). Resulting fire behavior predictions are pixel based and include fireline intensity (kW/m), heat per unit area (kJ/m^2), and flame length (m). Probabilities of fire occurrence can also be calculated using long term weather data. We used a cross walk table (Table C.1) between flame length and burn severity to estimate postfire soil burn severity and ground cover. The cross walk was determined within our group based on previous studies combined with the experience of the participants in the analysis. FlamMap was first used to predict burn severity for current conditions in the Mokelumne watershed. Fuel reduction treatments alter vegetation canopy and this impacts fire behavior, therefore FlamMap was run a second time to predict burn severity after proposed fuel reduction treatments.

Table C.1: Crosswalk table for converting FlamMap flame length to burn severity

	Flame Length (ft)			
burn severity prediction	0	0-4	4-8	8+
	Unburned	Low	Moderate	High

C.3.2 WEPP

WEPP (Water Erosion Prediction Project) is a process-based model that predicts runoff and sediment yields from planar hillslopes and small, unchannelized watersheds (Flanagan and Nearing 1995). The surface hydrology component of the WEPP model uses climate, soils, topography, and vegetation input files to predict infiltration, runoff volume, and peak discharge for each simulated storm. WEPP then uses these inputs and predictions to calculate rill and interrill erosion, as well as sediment deposition (Flanagan and Nearing 1995). Disturbed WEPP (Elliot 2004) is an online interface for WEPP designed to facilitate the use of WEPP in forested areas. Disturbed WEPP can simulate different forest conditions and management scenarios, including the effects of fuel treatments, and the model has been used to predict postfire erosion in forested areas (Soto and Diaz-Fierros 1998; Larsen and MacDonald 2007; Spigel and Robichaud 2007). The need to predict postfire erosion rates across the entire Upper Mokelumne watershed necessitated the use of the Geo-spatial interface for the Water Erosion Prediction Project (GeoWEPP) (Renschler 2003).

GeoWEPP facilitates the use of WEPP across large areas by converting GIS data into WEPP inputs, running WEPP, and then compiling the results into a spatial map (Renschler 2003). The various plant/management and soil input files developed for burned areas and used in the Disturbed WEPP interface were used to create the different sets of input parameters needed by the underlying WEPP model.

C.3.2.1 Development and compilation of input data

Prior to preparing the model, the authors visited the watershed to collect data at various elevations and forest conditions. These findings were then compared to the data compiled from other sources to ensure accuracy, with adjustments made as necessary. For the spatial WEPP modeling, the Upper Mokelumne watershed was divided into 305 sub-watersheds using a Digital Elevation Model (DEM) and ESRI watershed tools. Sub-watersheds were used to create smaller raster inputs (DEM, soil, landcover) for batch files. These batch files were then modeled in a batched version of GeoWEPP (Miller et al. 2011). In the cases where the sub-watersheds contained more than one drainage outlet or the model failed to run, the sub-watersheds were rerun using GeoWEPP for ArcGis 9.3. The resulting erosion prediction maps from the batch runs were then merged into the final erosion maps.

C.3.2.2 Climate data

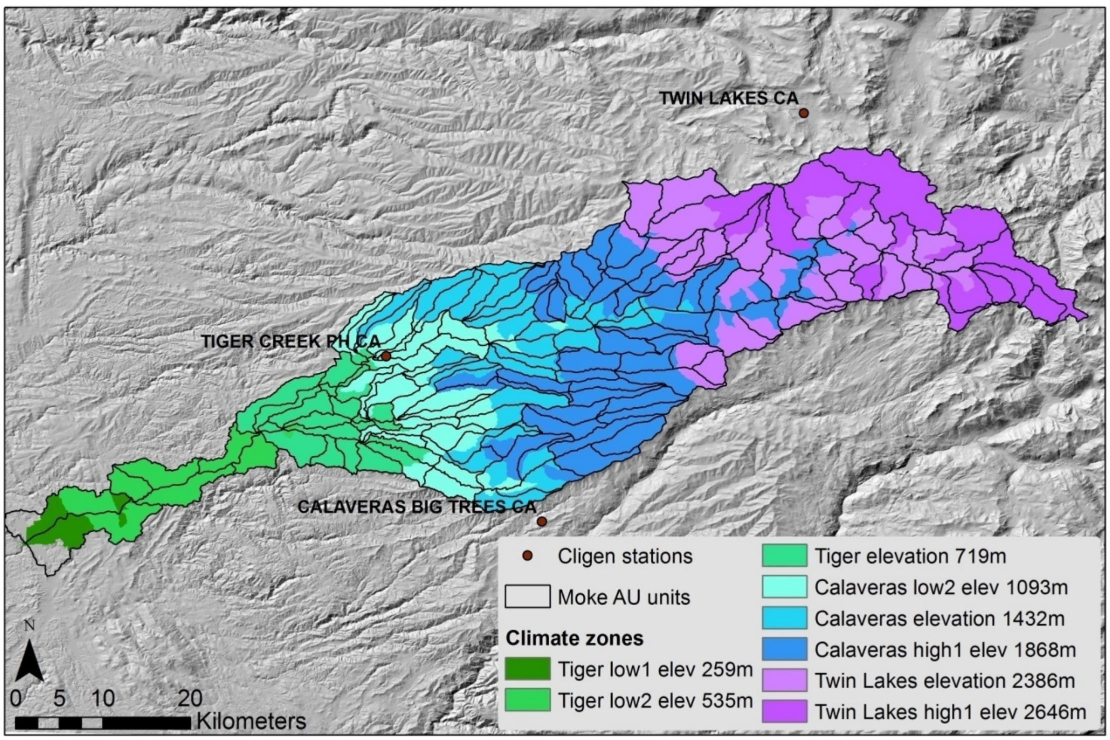
A key model input for predicting erosion rates is climate data; WEPP uses a stochastic weather generator called Cligen (Nicks et al. 2005) to generate the climate parameters needed to model run-off and erosion (mean daily precipitation, minimum and maximum daily temperatures, dew point, mean daily solar radiation, and mean daily wind speed and direction). Cligen has a database of more than 2,600 climate stations within the United States. The U.S. Forest Service has improved these climate parameters with Rock:Clime, an interface to Cligen which interpolates climate parameters between stations (Elliot et al. 1999; Scheele et al. 2001). This interpolation is particularly important in mountainous areas like the Mokelumne watershed because of the large changes in climate conditions that occur with changes in elevation, as well as the paucity of climate stations in these areas. The interpolation procedure in Rock:Clime modifies the data for a selected climate station based on elevation and PRISM data (Parameter-elevation Regressions on Independent Slopes Model). 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 et al., 2004).

Three Cligen stations are located within or near the Mokelumne watershed and these stations (Twin Lakes, Calaveras Big Tree, and Tiger Creek) were used to generate an additional five climates with the Rock:Clime interface. The additional climates were generated to account for the impacts of elevation changes in the watershed (Table C.2). Each climate file was created to contain 50 years of daily stochastically generated weather data. The average elevations of the initial WEPP sub-watersheds were then used to select the appropriate climate file (Figure C.1) for each sub-watershed.

Table C.2: Stochastically generated climate files for the Mokelumne watershed

Elevation Ranges	Climate Station	elevation	avg. annual precip
100m – 300m	Tiger low Rock:Clime Prism:	259 m	799 mm
300m – 600m	Tiger low2 Rock:Clime Prism	535 m	951 mm
600m – 900m	Tiger Creek station	719 m	1176 mm
900m – 1200m	Calaveras low Rock:Clime Prism	1093 m	1138 mm
1200m – 1500m	Calaveras Big Trees station	1432 m	1383 mm
1500m – 2000m	Calaveras Big Trees high Rock:Clime Prism	1868 m	1336 mm
2000m – 2400m	Twin Lakes station	2386 m	1249 mm
2400m +	Twin Lakes high Rock:Clime Prism	2646 m	1438 mm

Figure C.1: Distribution of climate forecasts within the Mokelumne watershed



C.3.2.3 Land cover and plant/management input files for WEPP

Landcover data were obtained from the LANDFIRE Project, a joint venture between the U.S. Department of Agriculture Forest Service and the U.S. Department of the Interior. LANDFIRE data layers include information on potential and existing vegetation, fire regimes, fire risk, surface and canopy fuels, topography, and disturbances (Rollins, 2009). For this analysis, we used LANDFIRE data updated based on field observations for the fire modeling runs. In addition to making the process more efficient through sharing data, this ensured consistency across the modeling efforts. We then reclassified the Existing Vegetation data layer into Disturbed WEPP cover types in order to model background erosion rates from the Mokelumne watershed without fire. For modeling postfire conditions, the FlamMap burn severity maps from before and after fuel reduction treatments were used to reclassify landcover into low, moderate, and high burn severity classes (based on Table C.1). In order to model the effects of the fuel reduction treatments, we used the map of the proposed treatments developed for this analysis.

C.3.2.4 Soils data

For the WEPP modeling, we used LANDFIRE soil layers that were derived from STATSGO (STATe Soil GeOgraphic) data (USDA 1991). This dataset included: maximum soil depth; percent rock fragments (> 2.0 mm); percent sand; percent silt; and percent clay. The percent sand, silt and clay layers were used to classify each soil pixel into one of the four soil texture classes represented in Disturbed WEPP (sandy loam, loam, silt loam, and clay loam). Disturbed WEPP input parameters (e.g., effective hydraulic conductivity, soil albedo, and rill erodibility) specific to each soil texture class were then used in the modeling (Elliot *et al.* 2000). Soil parameters also vary according to predicted burn severity and upon the type of vegetation.

C.3.2.5 Topographic data, watershed delineation, and processing

The DEM was downloaded from the National Elevation Dataset at a 30m resolution (Gesch et al., 2002; Gesch, 2007). GeoWEPP utilizes TOPAZ, Topographic Parameterization (Garbrecht and Martz 1999), in order to delineate watersheds and create the slope parameter files needed to run WEPP. Required input parameters for TOPAZ include the critical source area (CSA) and minimum source channel length (MSCL). We used the default GeoWEPP settings for these variables, 5 ha for CSA and 100 m for MSCL, which resulted in a mean hillslope size of about 6 ha.

C.3.3 Results

Erosion from hillslopes in the Mokelumne watershed was modeled and mapped under four distinct conditions. 1) Current vegetation conditions in the absence of fire; 2) after a fire assuming current fuel conditions; 3) after the fuel treatments and no fire; 4) and finally, fuel treatment conditions after a fire. When interpreting the results it is important to note that WEPP predicts one potential component of erosion: small soil constituents, 2 millimeters or smaller in size. The first condition determined background erosion rates without fire under the current vegetation conditions. Average erosion in the unburned basin was 0.67 Mg/yr^{-1}ha for the entire basin and 0.4 Mg/yr^{-1}ha in the lower treated section. Forested hillslopes typically did not generate significant erosion, but the steep, barren rocky slopes in the upper portions of the basin were highly erosive. The next run used the FlamMap predictions of burn severity under the current vegetation conditions to predict postfire erosion (Figure C.2). Average first year postfire hillslope erosion in the Mokelumne watershed was 32 Mg/yr^{-1}ha, much higher, more than 30 times, the unburned conditions. The mapped postfire erosion predictions were used by our committees to plan and prioritize a hypothetical fuel reduction treatment strategy within the basin. The application of these treatments, which included prescribed fire, biomass removal, and thinning, would also impact erosion rates within the watershed, so the effects of these treatments were modeled in our third run. Fuel treatments were only planned in the lower portions of the watershed and the average predicted erosion rate from these treatments was 0.69 Mg/yr^{-1}ha, an average increase of 0.02 Mg/yr^{-1}ha over no treatments. Canopy cover would change as a result of the treatments and the effect this would have on burn severity was modeled in FlamMap, the results of which were used to model first year postfire erosion. For the condition of modeled implementation of treatments following fire, the average postfire erosion rate for the whole watershed was 26 $Mg/yr^{-1}ha$, or 6 $Mg/yr^{-1}ha$ less than the average postfire erosion rates before treatments. In the second year postfire, erosion rates for both the current conditions and treated conditions are predicted to drop to only 10% of their first year postfire values, and return to pre-fire levels in year three postfire. A summary of erosion results and statistics for the entire watershed is found in Table C.3. If only the treated portions of the basin are summarized; the reduction in postfire erosion between the current conditions and treated runs is even greater: 20 $Mg/yr^{-1}ha$ (Table C.4).

Figure C.2: Predicted erosion for the first year postfire based on current vegetation

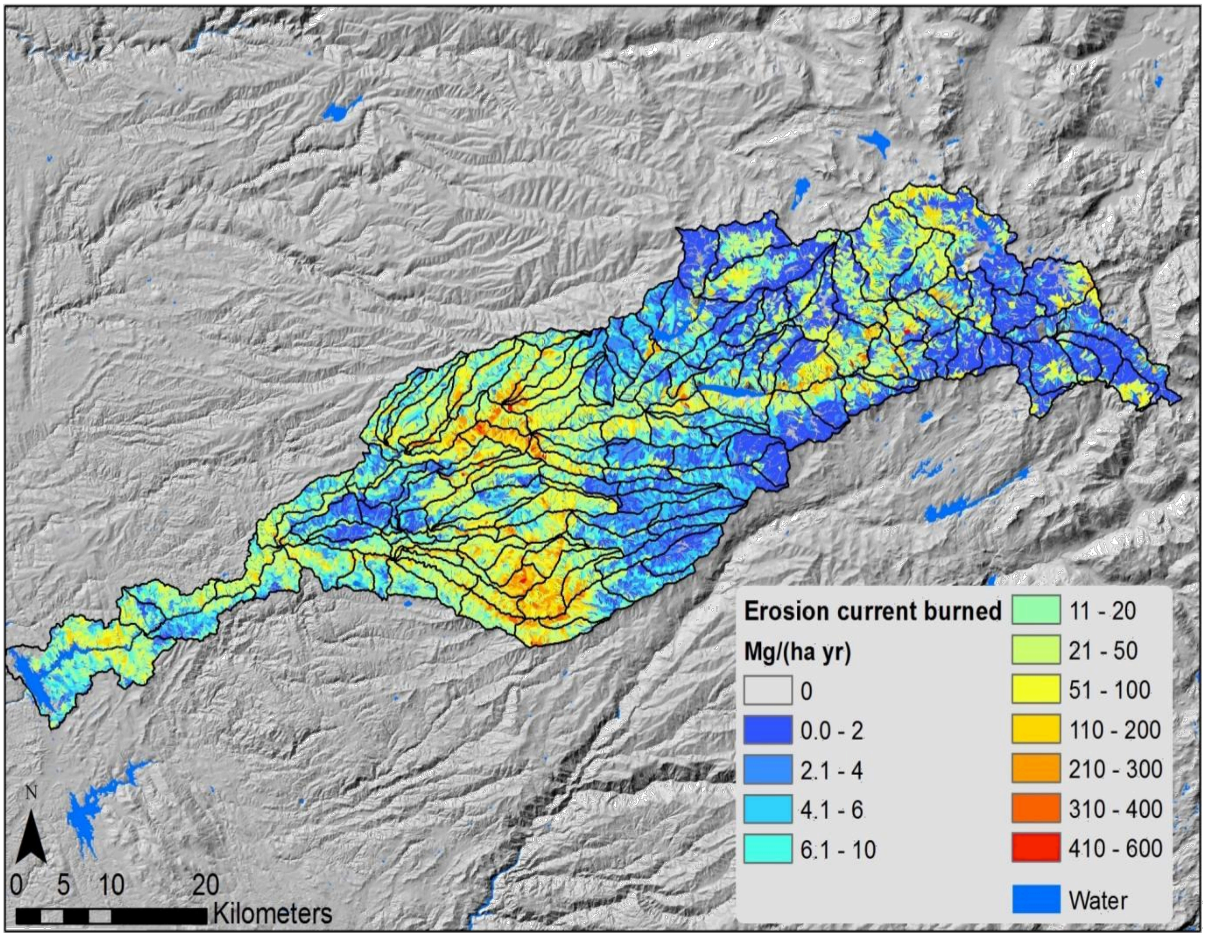


Table C.3: Summary of the results from four model runs for the entire Mokelumne watershed

	Current Condition	Fire Following Current Condition	Treatment Effects	Fire Following Treatment
Average Erosion in Basin	0.67 Mg/ha	32 Mg/ha in year 1	0.69 Mg/ha	26 Mg/ha in year 1
Range	0 – 84 Mg/ha	0 – 566 Mg/ha	0 – 84 Mg/ha	0 – 535 Mg/ha
Standard Dev	3.0 Mg/ha	55 mg/ha	2.5 Mg/ha	44 Mg/ha

Table C.4: Summary of results from four model runs for only the affected areas

	Current Condition	Fire Following Current Condition	Treatment Effects	Fire Following Treatment
Average Erosion in Basin	0.40 Mg/ha	46 Mg/ha in year 1	0.69 Mg/ha	26 Mg/ha in year 1
Range	0 – 84 Mg/ha	0 – 566 Mg/ha	0 – 84 Mg/ha	0 – 535 Mg/ha
Standard Dev	2.5 Mg/ha	69 mg/ha	2.5 Mg/ha	36 Mg/ha

Our predictions of both burn severity and postfire erosion rates are comparable to field and satellite derived measurements collected in or near the basin. Model validation of postfire erosion is very difficult given the high variability in erosion rates and uncertainties involved with predicting future fire effects and climate scenarios. However, the ratio of high, moderate, and low burn severity from the FlamMap derived predictions for postfire burn severity were consistent with a satellite-derived map of burn severity from the Power Fire that burned within the Mokelumne watershed in 2004. Field measurements of postfire erosion rates from the nearby Cannon Fire ranged from 2.5-15 $Mg/yr^{-1}ha$ (Robichaud et al. 2008) and the Cannon Fire site is drier than the Mokelumne watershed, with a mean annual precipitation of only 658 mm compared to the range of 799-1438 mm expected in the Mokelumne watershed. While this comparison does not validate our modeling, it does demonstrate our results are reasonable.

C.3.4 Frequency of burning

The fire behavior modelers also provided spatial predictions of fire probability for both current conditions and after the application of fuel reduction treatments. One of the benefits of fuel reduction treatments is a decrease in fire probability due to changes in fuels and canopy, note that probability of fire in a given year is fairly low. Figure C.3 is a comparison between (A) the first year postfire erosion under current conditions multiplied by current burn probability and (B) first year postfire erosion following treatments multiplied by burn probability after treatments. The negative areas on the map represent regions which are modeled to have a slightly higher burn severity after treatments, but overall the modeled treatments are predicted to decrease burn severity and postfire erosion. The average reduction in postfire erosion for the entire basin due to fire between the current conditions and post treatment was 0.05 $Mg/yr^{-1}ha$. This metric, however, does not allow us to examine the effects of the treatments on erosion rates in the absence of fire. In order to consider all four model runs we needed to look at long term (century scale) "average annual" erosion rates.

To develop predictions for long term "average annual" erosion rates in the watershed we needed to account for erosion in both fire and non-fire years, as well as the effects of treatments on erosion rates and burn probabilities. Under current conditions, the long term hillslope erosion rate ($\mathrm{Avg.\,Erosion_{cc}}$) can be represented by Equation 1. If we assume that the effects of the fuel reduction treatments last for 25 years, then Equation 2 could represent long term erosion rates ($\mathrm{Avg.\,Erosion_{tr}}$) with regular fuel reduction treatments.

$$\mathrm{Avg.\,Erosion_{cc}} = E_{cc\_fire} * bp_{cc\_fire} + \left(1 - bp_{cc\_fire}\right) * E_{nf} \qquad \text{(Eq 1)}$$

$$\mathrm{Avg.\,Erosion_{tr}} = E_{tr\_fire} * bp_{tr\_fire} + \left(1 - bp_{tr\_fire}\right) * (24 * E_{nf} + E_{tr})/25 \qquad \text{(Eq 2)}$$

Where:

E_{cc_fire} is the mapped postfire erosion rates for current conditions.

E_{tr_fire} is the mapped postfire erosion rates following fuel treatments.

E_{tr} is the mapped erosion rates due to the effects of the fuel treatments.

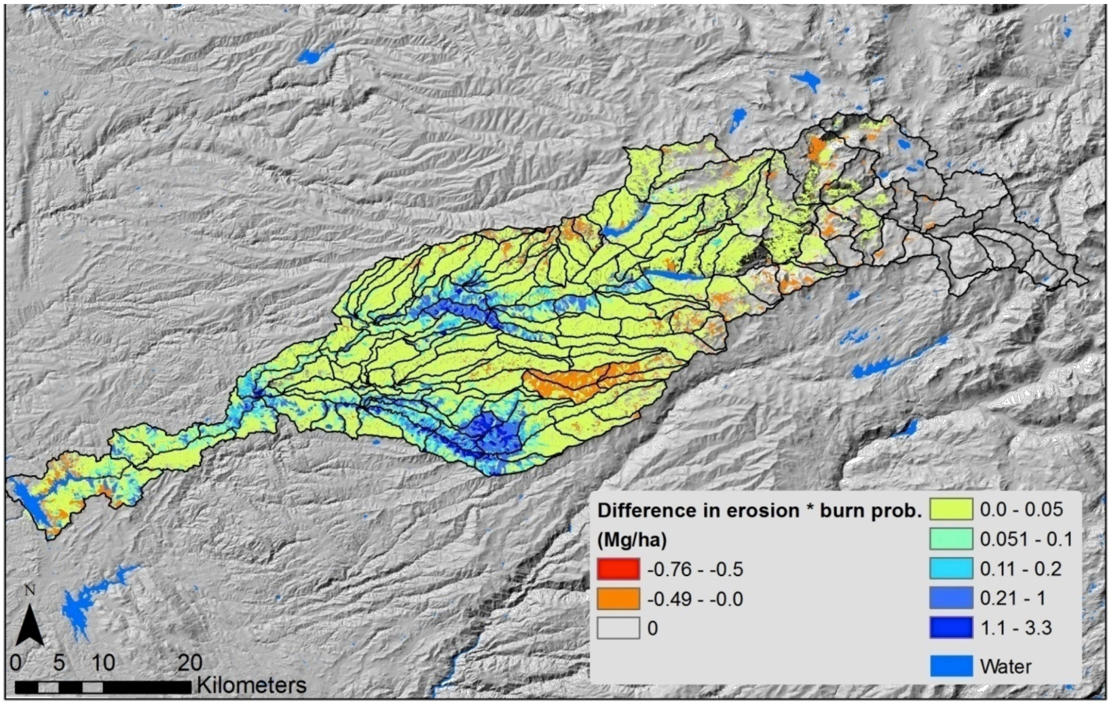
E_{nf} is mapped erosion rates for current conditions in the absence of fire.

bp_{cc_fire} is the mapped probability of fire under current conditions.

bp_{tr_fire} is the mapped probability of fire following fuel treatments.

These equations were used in conjunction with our four model runs to develop long term "average annual" erosion rates for the treated portions of the watershed with and without fuel reduction treatments every twenty five years. Model results for long term average erosion rates for current conditions were 0.64 $Mg/yr^{-1}ha$, compared to 0.52 $Mg/yr^{-1}ha$ if the designated treatment area is in fact treated as modeled. Our predictions indicate that regular treatments will significantly reduce long term overall erosion rates by lowering "average annual" erosion rates by 19%.

Figure C.3. Difference between postfire erosion predictions for current conditions x burn probability for current conditions and posttreatment x burn probability posttreatment



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Appendix D: Debris Flow Modeling

D.1 Introduction

Debris flows can be one of the most dangerous consequences of rainfall on steep terrain recently burned by wildfire. The probability of a post-fire debris flow occurring is low as most burned watersheds will produce sediment laden flows (as discussed in Appendix C) in response to heavy precipitation; however basins that are prone to debris flows warrant special attention due to the extreme risk they pose to life and property (Cannon et al. 2010). In order to gauge the impact the modeled fuel reduction treatments would have on debris flows in the basin, we modeled the probabilities and potential volumes of post-fire debris flows before and after fuel reduction treatments. Modeling was carried out using empirical models developed by the United States Geological Survey (USGS) to assess post-fire debris flow threats in the intermountain west (Cannon et al. 2010). We predicted a 12% decline in potential post-fire debris flow volume and a 27% reduction in debris flow probability in the portions of the watershed with modeled treatments. The predictions of potential post-fire debris flow volumes ranged from 0 to 640,000 m^3. Our predictions were well within the range of the field observations of debris flow volumes from 55 recently burned basins. These basins burned in 8 different fires in Colorado, California and Utah and measured debris flow volumes ranged from 174 to 864,300 m^3 (Cannon et al. 2010).

D.2 Modeling approach

A GIS tool was created to apply two empirical models to small sub-basins over large spatial areas. These models were generated from datasets gathered from 388 basins that burned in 15 different fires in the intermountain western US states (Cannon et al. 2010). The first equation used slope, burn area, and total storm precipitation to estimate mean volume (V, in m^3) of material deposited by a debris flow (Cannon et al. 2010). Equation 2 predicts the probability that a debris flow will occur (P) in a given basin (Cannon et al. 2010). Model inputs included a Digital Elevation Model (DEM) to determine slope and roughness, a delineation of sub-basins, storm intensity and total rainfall, clay percentage and liquid limit of soils, and a burn severity map. Storm intensities and total rainfall were derived from a series of spatial NOAA design storms. DEM and soil parameters were derived from the National Map and from STATSGO. The FlamMap derived burn severity maps (Appendix A) were used to represent post-fire conditions for before (current conditions) and after fuel reduction treatments. Modeling results from the debris flow probability run for current conditions could serve as a post-fire debris flow hazard risk map. The models are as follows:

$$\mathrm{V} = \exp(7.2 + 0.6 * lnA + 0.7 * \sqrt{B} + 0.2 * \sqrt{T} + 0.3) \qquad \text{(Eq 1)}$$

Where A represents the area (km^2) of the sub-basin with slopes that are greater than or equal to 30%, B represents area (km^2) of the sub-basin burned at moderate or high severity, and T represents the total storm rainfall (mm).

$$\mathrm{P} = \frac{\exp(-0.7 + 0.03 * \%A - 1.6 * R + 0.06 * \%B + 0.07 * I + 0.2 * C - 0.4 * LL)}{1 + \exp(-0.7 + 0.03 * \%A - 1.6 * R + 0.06 * \%B + 0.07 * I + 0.2 * C - 0.4 * LL)} \qquad \text{(Eq 2)}$$

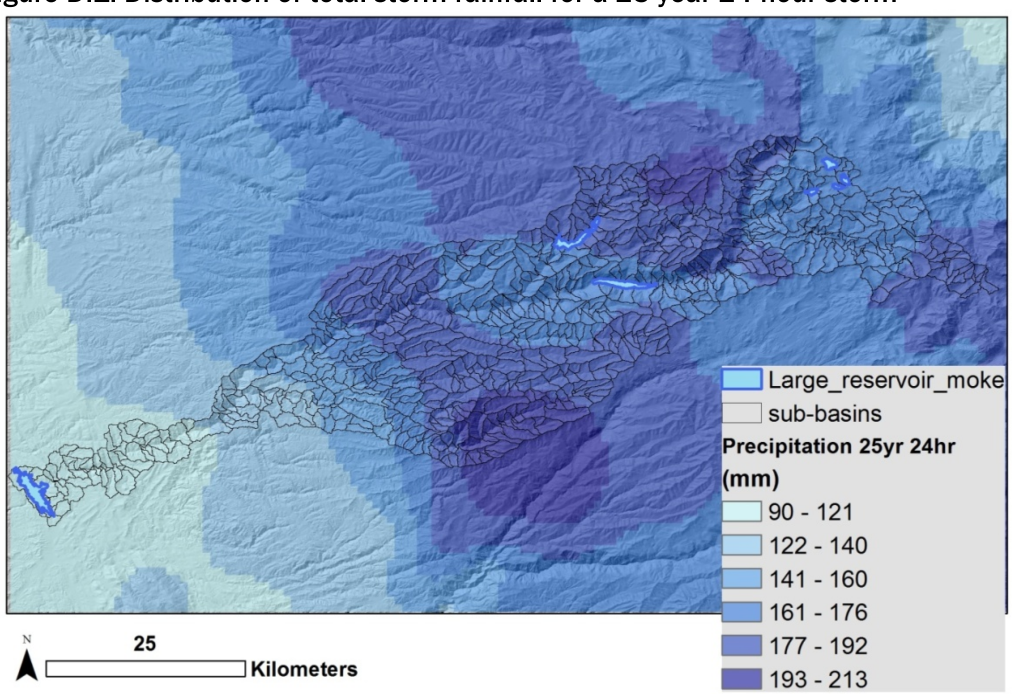
For predicting probability of debris flow occurrence, %A represents the percentage of the sub-basin with slopes greater than or equal to 30%, R represents sub-basin ruggedness – change in elevation divided by square root of the area (Gartner et al. 2008), %B represents the percentage of area burned at moderate or high severity, and I represents average storm rainfall intensity (mm/hour). The two soil parameters are C, the percentage of clay content in the soil, and LL, the liquid limit. Liquid limit is a measure of the moisture content required to change soil behavior from plastic to liquid.

The two empirical models (Eq 1 and 2) were applied spatially using a watershed delineation that contained 776 sub-basins. The smaller scale delineation was needed in order to ensure the areas of each sub-basin were not larger than the basins used in generating the empirical models, thus ensuring that the models were applied in a manner consistent with how they were designed to operate.

D.2.1 Climate data

The Debris Flow model uses storm data rather than the daily weather parameters used by the WEPP model. Gridded NOAA precipitation frequency estimates for California (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html) were used to generate storm intensity and total precipitation. The grids are available for a variety of storms ranging in duration from five minutes through 60 days and for storm return intervals from 1 to 1,000 years (Bonnin 2004). The grids contain total storm precipitation; therefore in order to obtain storm intensity we divided the total rainfall by the storm duration. Zonal statistical tools were used to obtain the average rainfall for each sub-basin. We modeled five storms with a variety of return intervals and duration periods in order to capture storms with high intensities (shorter duration) and storms with high total rainfall (Figure D.1 displays one of the five storms).

Figure D.1: Distribution of total storm rainfall for a 25 year 24 hour storm



D.2.2 Land cover and plant/management input files for Debris Flow modeling

For the Debris Flow model, the only landcover inputs needed were the FlamMap results (derived burn severity maps, see Appendix A) for before and after fuel treatments. Our GIS tool used zonal statistics to calculate the area of each sub-basin predicted to burn at moderate and high severity. This input was the only variable to change between the two sets of model runs.

D.2.3 Soils data

The soil parameters needed for the Debris Flow modeling included the percentage of clay in the soils and the liquid limit of the soil. These parameters were obtained directly from the STATSGO2 dataset (Soil Survey Staff 2013) using the Natural Resource Conservation Service Soil Data Viewer to obtain maps of both parameters. These parameters could vary spatially across the sub-basin, so they were also averaged using zonal statistics.

D.2.4 Topographic data, watershed delineation, and processing

Our DEM was downloaded from the National Elevation Dataset at a 30m resolution (Gesch et al., 2002; Gesch, 2007). The DEM was used to create our watershed delineation and derive the required slope input using ESRI ArcGIS tools. Surface roughness was also derived from the DEM using zonal statistics to find the maximum and minimum elevation in each sub-basin.

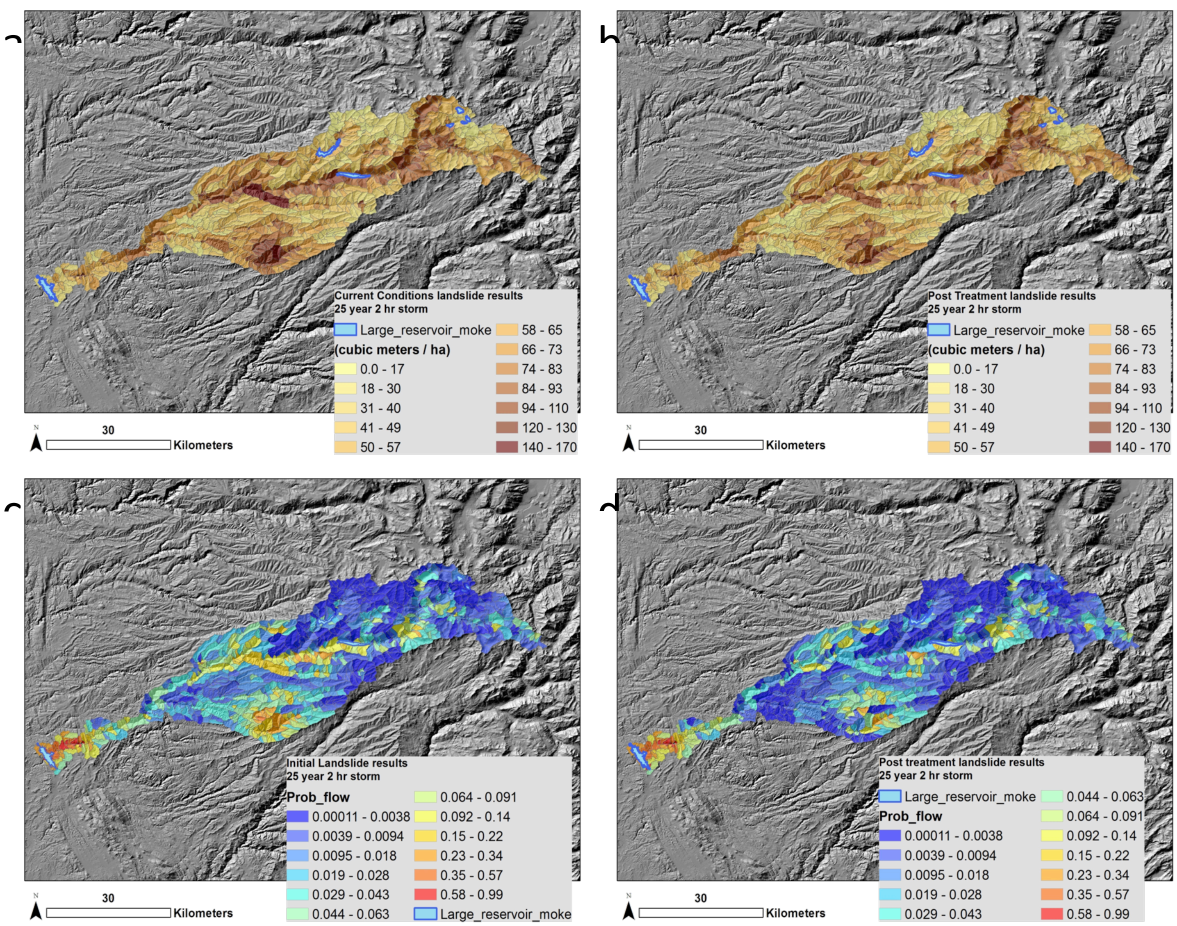
D.3 Results

We modeled five different storms in order to obtain a range of parameter values for total storm precipitation and intensity (Table D.1). Storm intensities for longer duration storms were low as they represented average intensities over the entire storm. To obtain higher intensity values in the basin, we modeled a shorter one-hour storm. Longer duration storms could easily have periods of high rainfall intensity, which would not be represented by an averaged intensity value. The longer duration storms generated higher total precipitation amounts and therefore higher predicted debris flow volumes. Shorter duration storms generated higher storm intensity values and hence higher probabilities of debris flow occurrence, but with smaller predicted volumes than longer duration storms (Table D.1). The probability of a post-fire debris flow event in an individual sub-basin is low, generally less than 1% (Table D.1, Figure D.2). However, if the entire watershed were to burn, the likelihood of a debris flow event occurring within the watershed would increase dramatically as there are several hundred sub-basins. For each sub-basin, we predicted debris flow volume and probability both before and after the modeled treatments. These results were then averaged for sub-basins in or neighboring the fuel reduction treatments (Table D.1). Based upon the modeling results, the modeled fuel reduction treatments did reduce both volume and probability of debris flows within the watershed. Post-fire debris flow volumes in the treated portions of the watershed are predicted to decrease by 12% and the probability that a debris flow would occur decreases by 27%.

Table D.1: Mean debris flow predictions for 313 sub-basins in or neighboring modeled fuel reduction treatments in the Mokelumne watershed.

	Avg Volume (m^3/ha)			Avg Probability in %		
Storm	Before treatments	Post treatments	Percent change	Before treatments	Post treatments	Percent change
2 year 2 hour	46	41	11%	0.059	0.044	25%
10 year 24 hour	187	163	13%	0.047	0.036	23%
25 year 1 hour	54	48	11%	0.14	0.090	34%
25 year 2 hour	64	57	11%	0.089	0.062	30%
25 year 24 hour	230	201	13%	0.049	0.037	24%
		mean	12%		mean	27%

Figure D.2: Debris flow modeling results for a 2 hour storm with a 25 year recurrence interval. Maps of predicted debris flow volumes (m^3/ha) a) before modeled fuel treatments and b) after modeled treatments. Probability maps of debris flow occurrence c) before modeled fuel treatments and d) after treatments.



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Appendix E: FERGI - Estimated Postfire Gully Erosion in the Mokelumne Watershed

E.1 Abstract

The Fire-Enhanced Runoff and Gully Initiation Model (FERGI) was used to estimate the amount of sediment that might be produced from gully erosion in the Mokelumne watershed following large wildfires under both the no-treatment and post-treatment scenarios. FERGI estimates the probability of runoff generation and gully initiation on hillslopes after fires. The model uses stochastically generated weather time series as inputs to determine the probability of particular outcomes. Results include return intervals for runoff generation rates and totals, upslope extent of gully initiation (channel extension), and the changes that might be expected with fuels treatments.

E.2 Model Purpose

After fires, water repellency can decrease the infiltration capacity of soils (for example, DeBano, 1981) and the loss of surface organics can increase the mobility of soil particles. Together these effects increase the likelihood of runoff and erosion compared to unburned conditions, particularly during intense thunderstorms. In response to the increased risk of runoff and erosion, land managers and technical specialists sometimes apply erosion control efforts to reduce the consequences. Because of the brief window of time that risks are increased, and because of the strong dependence of fire related erosion on severe weather events, empirically demonstrating the effectiveness of these treatments has thus far proven to be an elusive task.

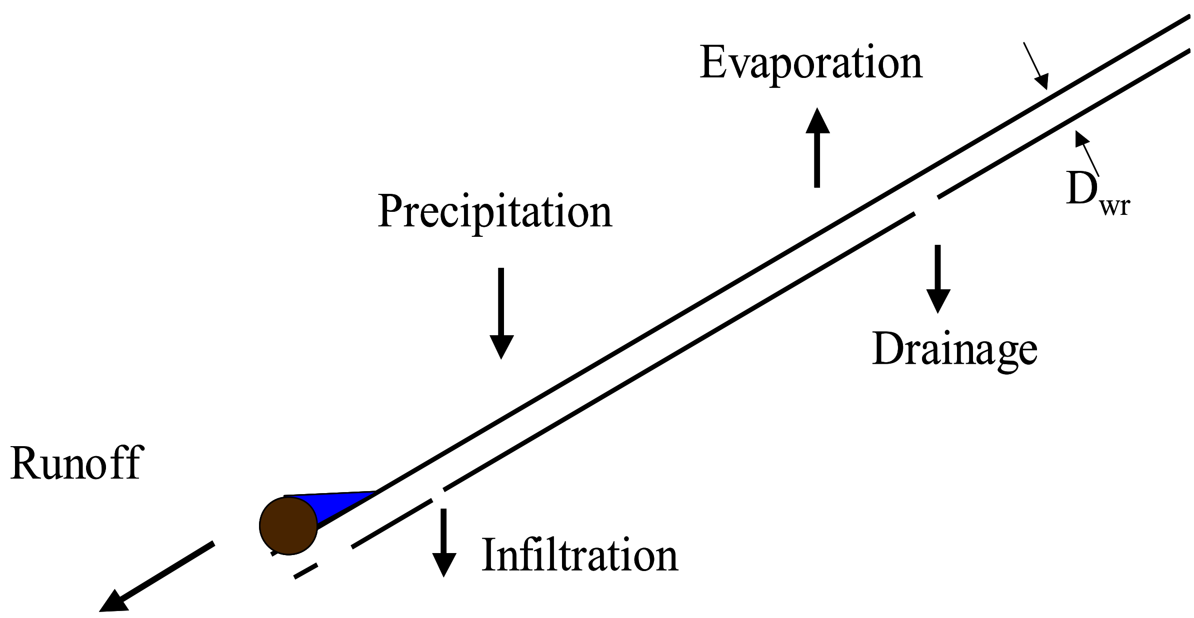
In part, the problem is that the effectiveness is not a constant percentage reduction or some similar parameter, but depends on the amount and intensity of rain received. For very tiny storms, treatments do nothing. Conversely, they can be overwhelmed by large storms. For a range of storms between these extremes, we would expect a varying degree of effectiveness. Quantifying an estimate of this effectiveness function is most efficiently done using simulations. Such simulations require an accurate, physically based mathematical description of the hillslope hydrologic and geomorphic response to a given set of weather events and a means for describing the potential series of weather events (e.g. a stochastic weather model). The resulting output provides an estimate of the effectiveness as a function of storm return periods.

E.3 Model Design

FERGI comprises a stochastic climate generator and a deterministic hillslope hydrology and geomorphology model. The stochastic climate generator model is a k-nearest neighbor resampling model based on Rajagopalan and Lall (1999). It simulates daily sequences of precipitation and temperature using information from the preceding day's precipitation and temperature and a set of similar days drawn from the historical record. Once the daily precipitation total is estimated, a second resampling draws from the 15-minute precipitation data set for days with similar precipitation totals within an 18-day window, and wind speeds are similarly selected from a separate wind speed data set. The stochastic data are fed to a hydrology model.

The water repellent layer that may form after fire is generally underneath a shallow wettable layer (< 10 cm thick) of soil (DeBano, 1981). The water repellent layer is discontinuous, allowing water to penetrate through regions with lower repellency. FERGI calculates the water balance of the thin wettable layer of soil overlying the water repellent layer of depth D_{wr} (Figure E.1). The model shares its physical basis with the conceptual approach proposed by Shakesby and others (2000), and goes a step further in numerically estimating the components of the water balance given driving weather. The water balance of the thin layer is maintained with both short term and long term components (Figure E.1). The long term components include drainage and evaporation that reduce the water content of the layer over days. Potential evaporation is based on daily climate simulation and modified by the water content of the surface layer. Drainage brings the surface water content to field capacity by the end of each day. The short term components are precipitation and infiltration that occur during brief precipitation events. Precipitation is provided by the stochastic climate generator as a series of intensities and durations. Infiltration capacity is estimated as the mineral soil saturated hydraulic conductivity multiplied by the fractional water repellent area. Contour felled logs add a component of surface storage and decrease the fractional water repellent area. Runoff is precipitation that is excess to infiltration and storage within the shallow layer. Runoff is routed using a kinematic wave approach to estimate the depth of flow as a function of contributing hillslope distance and, consequently, shear stress. The shear stress is compared to critical shear stress for initiation of particle motion to estimate where gullies might initiate during an event (Istanbulluoglu and others, 2002).

Figure E.1: Schematic of the hillslope hydrology in FERGI.



E.4 Running the Model

The user is asked to specify the weather stations used for the stochastic climate simulation and to supply some simple soil and hillslope information for the model runs. Climate station selection is accomplished in an ArcIMS environment so that users can select stations that are near the site geographically and most similar to the site climatically in their judgment. Soil characteristics that need to be estimated are median grain size and mineral soil hydraulic conductivity, for which there are published relationships to soil texture. In addition, they will be asked to supply the fractional water repellency for the area and the average depth to the water repellent layer, which can be measured or estimated. Fractional water repellency and depth to the water repellent layer were estimated based on previous work in diverse settings that all had roughly the same results. Despite substantial differences in bedrock and soil structure, sites in Idaho and Montana showed very similar patterns in fractional water repellent area immediately after fire and declining with time. Under severe conditions fractional water repellency ranged from 90 to 99% on 100-m transects. Averaging across many transects for particular study units, numbers were close to 95% in several locations as first-year water repellency. These results were partially published and discussed in Luce et al. (2012). The model results were relatively insensitive to depth to water repellent layer within a reasonable range.

The slope and average hillslope length before channel inception complete the list of information needed about site characteristics. Information needed about treatments consists of the amount of surface water detention provided by treatments and the areal fraction of the hillslope that is trenched, perforating water repellent layers. Guidance is provided for all inputs.

Output from the model is provided as graphs and tables that can be put into graph making programs such as Excel. The amount of runoff and location of potential gully initiation points will be key metrics.

E.4.1 Description of gullies resulting from post-fire storm in December 2005

Field measurements of two gullies that formed during a major storm shortly after the Power Fire, a 17,000 acre fire that burned within the Mokelumne watershed in 2004, were made by Alan Janicki of the Stanislaus National Forest, and provide a basis for estimating the dimensions of gullies that might be initiated following a major wildfire as modeled using FERGI. Both gullies were observed within a salvage sale unit. As reported by Janicki (written commun., 2006):

"The lower half of the unit has a gully that has downcut into deep non-cohesive loamy material, possibly an old landslide deposit. The subsoil appears to be particularly erodible. The gully has two segments referred to as the upper gully and the lower gully. The upper gully is 125 ft long and averages 6 ft deep by 13 ft wide. The lower gully is 175 feet long and averages 5 ft deep by 10 ft wide. Both gullies have incised channels on relatively steep slopes. The slopes are 18% and 27% where the lower gully has cut its channel. The upper gully is located on a 21% slope. Approximately 700 plus cubic yards of soil has been removed by the two gullies. Both gullies are unstable and have potential for further headcuting during large storm events."

The storm that apparently initiated these gullies in late December 2005 was approximately a 10-year 24-hour storm. The design storm used in the FERGI model was a 2.5 year storm. Therefore, the gully dimensions measured in the field likely overestimate the dimensions of gullies generated by a storm of the intensity and duration used in the FERGI model. However, these were the only measurements available for post-fire gullies in the Mokelumne watershed, and their dimensions were used in conjunction with FERGI results as described below to estimate post-fire gully sediment production for the no-treatment and post-treatment scenarios.

E.4.2 Post-fire No-Treatment Scenario

FERGI results for the post-fire no-treatment scenario indicate a total of 181,232 30-meter pixels with gully erosion or channel extension. These results were converted to aggregate erosion volume and mass using the average dimensions of gullies measured after the Power Fire, which had average width of 11.5 feet and average depth of 5.5 feet. Based on photographs of the gullies observed in the field, the actual channel cross sections more closely resembled rectangles. Average cross-section gully area was therefore 63 square feet, or 5.9 square meters, assuming a rectangular channel shape.

For a rectangular channel, total erosion volume per 30-meter pixel is computed as average cross-sectional area multiplied by the 30-meter width of the pixel, or 176 m^3. Assuming a reasonable bulk density of 1.5 Mg/m^3, total erosion mass per pixel is 265 Mg, or metric tons. Multiplying by the total number of eroded pixels (181,232) gives a total of 47,946,868 Mg. Using a drainage basin area of 1,500 km^2, the gully-related sediment yield is 31,965 Mg/km^2 or 320 Mg/ha.

E.4.3 Postfire Treatment Scenario

FERGI results for the postfire treatment scenario indicate a total of 85,282 30-meter pixels with gully erosion or channel extension. These results were converted to aggregate erosion volume and mass as described above using the average dimensions of gullies measured after the Power Fire.

For a rectangular channel, total erosion volume per 30-meter pixel is estimated, as described above, at 176 m^3. Assuming a reasonable bulk density of 1.5 Mg/m^3, total erosion mass per pixel is 265 Mg, or metric tons. Multiplying by the total number of eroded pixels (85,282) gives a total of 22,562,267 Mg. Using a drainage basin area of 1,500 km^2, the gully-related sediment yield is 15,042 Mg/km^2 or 150 Mg/ha.

E.5 Comparison of Scenarios

The estimated post-treatment sediment yields for gully erosion, for either channel shape, are roughly 47% of the yields for the no-treatment scenario. The model therefore predicts that treatments to reduce fire severity would reduce post-fire gully erosion by 53% for the design storm. As noted above, these estimates are based on gully dimensions resulting from a higher magnitude storm, and may therefore be higher than sediment yields for a 2.5 year storm.

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Rajagopalan, B., and U. Lall. 1999. A k–nearest-neighbor simulator for daily precipitation and other weather variables. Water Resources Research **35**:3089-3101.

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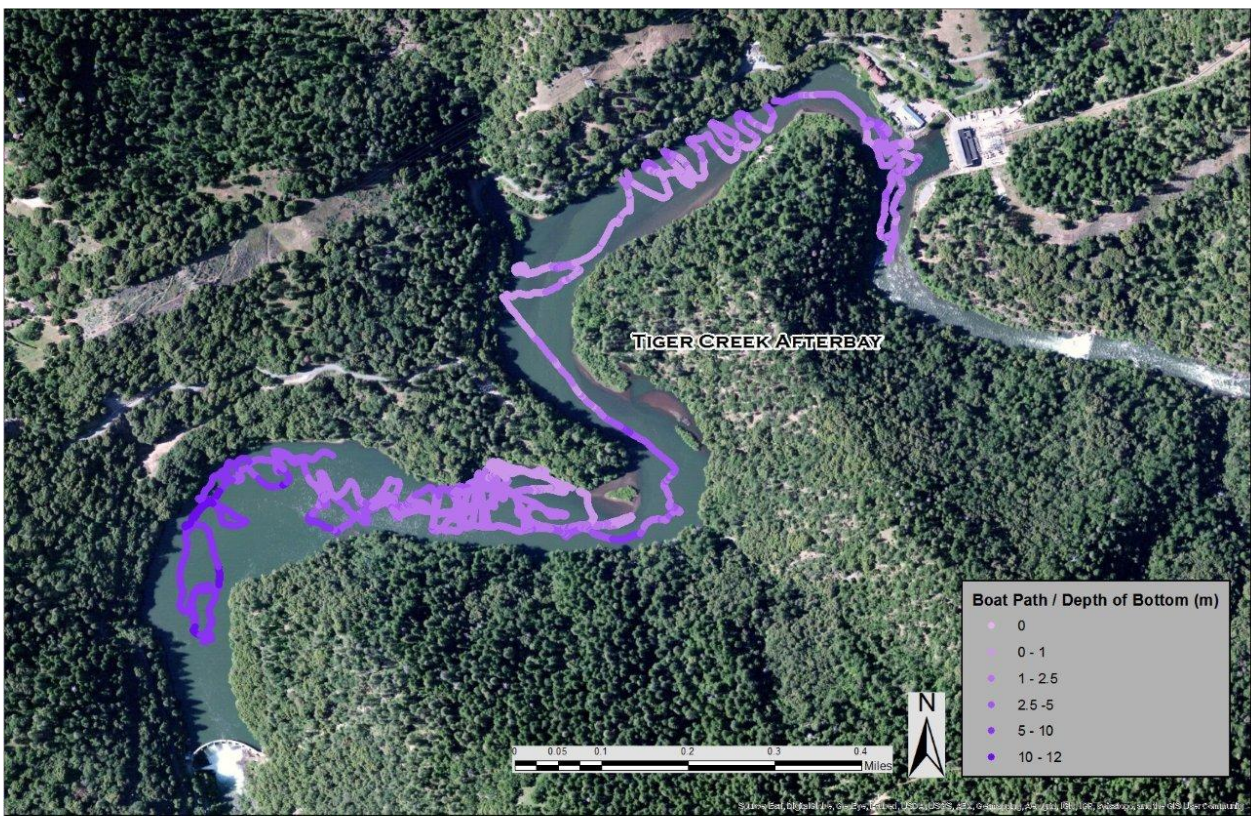
Appendix F: Bathymetric Survey - Methods for Calculating the Volume of Tiger Creek Afterbay

On September 5, 2013, Barry Hill, Nic Enstice, and Matthew Bokach surveyed the floor of Tiger Creek Afterbay with a customized radio-controlled bathymetric survey boat produced by Seafloor Systems Inc. Tim Tamplin from Seafloor Systems Inc. was also present. The survey was hampered by some logistical constraints including: the need to keep the boat within reasonable sighting distance; attempting to gain maximal coverage within the limited battery life of the boat; and PG&E's prohibition of any sort of manned boat within the reservoir. Due to these constraints, the closest we were able to get to the downstream dam wall was about 144 meters (Figure F.1). Being mindful of the battery life, our overall strategy was to conduct transects perpendicular to the flow of water in wider areas of the reservoir and collect a single track of data down the center of the reservoir in narrower areas.

Figure F.1: Tiger Creek Afterbay with the purple indicating the data collection point/path of the boat. The darker the purple, the deeper the bottom (in meters).



The shoreline of the reservoir was digitized by starting with the polygon from the National Hydrography Dataset and modifying it to match the treeline visible in a 1-m resolution National Agriculture Imagery Program aerial photograph taken in 2010. Our observation while walking nearly the entire length of the reservoir was that the treeline was very close to the edge of the water. However, because of the presence of "tree islands" within the reservoir and/or depths that were too shallow to run the boat, there were some small areas along the edges (particularly in the center of the reservoir) that were not included in the digitized polygon. The volume of water contained in these areas was estimated by a different process explained below. The shoreline polygon had an area of 205,403 m^2, or 50.66 acres. We converted this polygon to a set of points spaced every meter around the polygon perimeter. The depths of these points were set to 0 everywhere except along the dam wall and at the outflow structure at the upstream end of the reservoir. Depths at these points were set equal to the nearest bathymetric point collected.

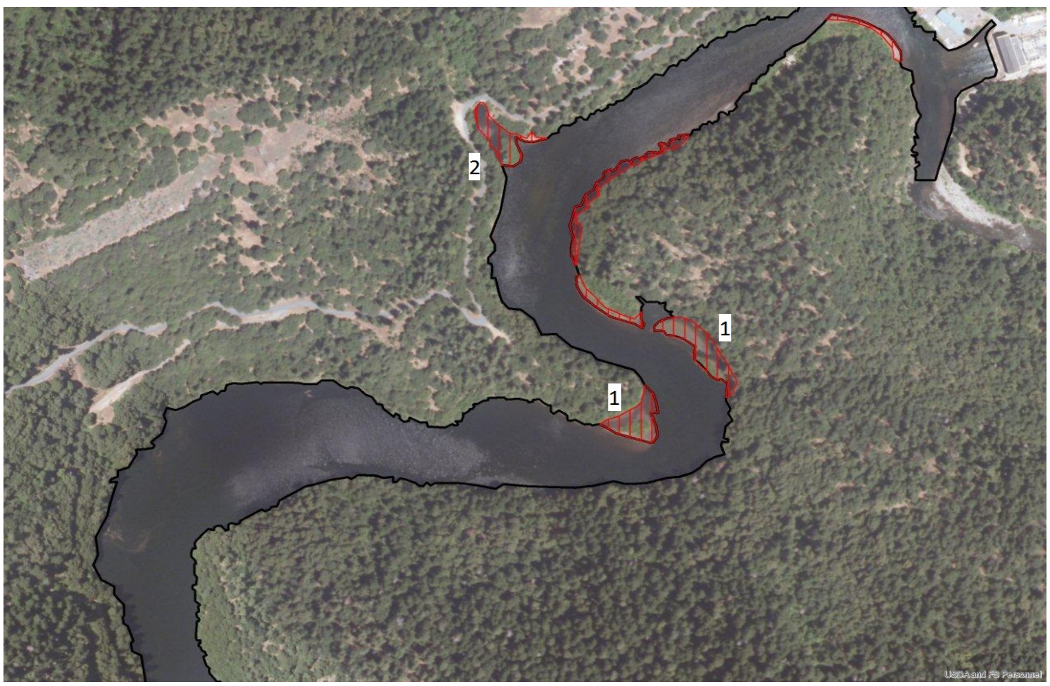
Following their collection in the field, in the office the bathymetric points were "cleaned" visually by looking at them in three-dimensions relative to a polygon of the reservoir surface that was defined as depth = 0. The cleaning heuristic was a smoothing one where points that deviated horizontally from the path of the boat were removed, as well as any points that introduced noticeable vertical discontinuities. Most of the removed points represented either: a) expected "drift" due to the time interval of GPS collection being faster than that of sonar collection; or, b) data collected when the boat was stationary (e.g., near shore or during downtime as operators were discussing their strategy). Tim Tamplin also indicated that the amount of vegetation visible at the bottom of the reservoir would reduce the accuracy of the sonar data, although the smoothing nature of the cleaning heuristic should have removed much of this "noise" from the data. Finally, any survey points that fell outside the digitized shoreline of the reservoir were removed. After cleaning, 24572 (54.9%) of the original 44792 points remained.

The bathymetric survey took place between 10:14am and 3:35pm. Stage readings collected every half hour during this time period and acquired from Chris Bennett at PG&E indicated that the stage level dropped linearly (r^2 = 0.9997) from 710.3486 meters above sea level to 710.0956 meters above sea level during this period. The regression equation relating stage to time was used to convert the sonar depths to elevations. Sonar depths were subtracted from the stage corresponding to the time of depth data acquisition to provide elevations for the lake bed. Shoreline points at depth = 0 were set to 710.3486 meters.

The Inverse-Distance Weighted (IDW) tool in the Spatial Analyst toolbox of ArcGIS was used to interpolate a three-dimensional surface of the reservoir's floor. The inclusion of zero-depth points along the shoreline forced the interpolated surface upward along the edges. Due to the inadequacy of the collected points to interpolate the entire area of the reservoir, points were densified by dropping lines between shoreline points and their nearest bathymetric points, and interpolating depths linearly at either the quintiles of these lines (i.e., four evenly-spaced points per line); or, in the case of lines that were longer than 80m, at the deciles (i.e., nine evenly-spaced points per line). The initial set of such lines were created at shoreline points spaced every 50m around the perimeter, and subsequently densified by half the distance iteratively, until enough such points had been created within an area that the IDW tool could interpolate a surface for the entire area of the reservoir. For most of the reservoir, these densification lines were needed every 12.5 meters until enough were present to interpolate the surface. In all, 1532 such "interpolation" points were required. The resulting interpolated surface covers 95.7% of the area of the shoreline polygon.

The reservoir volume was estimated by subtracting the interpolated floor surface from the zero-depth elevation of 710.349 meters. To estimate loss of capacity since the reservoir was created in 1931, we had to adjust this base elevation to match the 1931 crest of 713.232 meters above sea level. We added the additional 2.883 meters of water to the entire digitized polygon, and also added the areas around the edges that would be inundated at this higher stage[1] plus the 4.3% of the polygon that was not included in the interpolated surface (an additional 15,166 m^2) at the same depth (Figure F.2). This resulted in an estimated volume (at a stage of 713.232 meters) of 1,158,974.1 m^3. Compared to the 1931 capacity estimate of 4,884,588 m^3, this represents a loss of 76.3% of the reservoir's capacity since its creation (Table F.1).

Figure F.2: Tiger Creek Afterbay with red-hashed areas that were added in the digitization process to approximate the shoreline at original capacity.



[1] To calculate the higher stage, we used the same NAIP image to digitize the inundated portions of the reservoir that were not included in the main polygon. This included the areas behind the "tree islands" (1's on map), and a "pseudo-bay" that extends to the north (2 on map).Our working assumption was that the treeline reflects the area not consistently inundated for roughly the last 30 years, and hence the present water level is indicative of the overall average water level for the past couple decades. Unfortunately the Digital Elevation Model (DEM) data suggested that the reservoir is smaller than it presently is when we adjust for the stage to be at the 1931 level. Therefore, the treeline and the current inundation levels were all we could rely upon to estimate the appropriate shoreline.

Table F.1: Tiger Creek Afterbay estimated capacity based on 2013 bathymetric survey.

Reservoir	*Date Built*	*Drainage area (km2)*	*Initial Capacity (m3)*	*Estimated 2013 Capacity (m3)*	*% capacity*	*Sedimentation (m3)*
Tiger Creek Afterbay	1931	932.4	4,884,589	1,158,974.1	24%	3,725,614.9

In 2009, Minear and Kondolf[2] published a study on estimating sedimentation rates within reservoirs in California. Applying their methods to Tiger Creek Afterbay, we calculated a remaining capacity of 1,812,021 cubic meters, which is just over 10% more capacity than we calculated via the bathymetric survey. Both methods have their levels of uncertainty and assumptions, but the close proximity of the two independent results suggests that it is likely that Tiger Creek Afterbay has less than 50% capacity remaining. A more rigorous bathymetric survey of the Afterbay would help refine the estimate.

Table F.2: Tiger Creek Afterbay estimated capacity based on a study by Minear and Kondolf[2].

Reservoir	*Initial Capacity (m3)*	*Sedimentation rate (m3/km2/year)*	*Estimated 2012 Capacity (m3)*	*% capacity*	*Sedimentation (m3)*
Tiger Creek Afterbay	4,884,589	97	1,812,021	37%	3,072,568

[2] Minear, J. T., and G. M. Kondolf (2009), Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California, Water Resour. Res., 45, W12502, doi:10.1029/2007WR006703.

Appendix G: North Fork Mokelumne River Sediment Budget Analysis

G.1 Introduction

A key part of this analysis is an assessment of the relative importance of sediment sources that have already contributed to the filling of existing water and energy impoundments, specifically the PG&E Tiger Creek Afterbay. One sediment source is from mass wasting (landslides), which was discussed in the previous chapter in the context of possible future events. However, a number of landslides are apparent on aerial imagery in the project area and other smaller landslides (too small to be visible on aerial imagery) are documented in the area. The visible landslides are nearly all in the canyon of the North Fork Mokelumne, on the north side of the river near PG&E hydropower infrastructure (canals, pipelines, and holding ponds). Exact causes of these landslides are not documented but one possible cause or contributing factor could be water leaking from the hydropower infrastructure. Site-specific documentation regarding smaller landslides is available, which are usually associated with a specific project or road maintenance need. While large landslides visible on aerial imagery have been mapped, there has not been a comprehensive landslide inventory, including small landslides across the project area.

Photo evidence of landsliding is sparse, although this appears to be the result of the difficulty in capturing the relatively small scale of landsliding (compared to the Klamath Mountains or Coast Ranges) rather than a lack of landsliding. This is supported by the fact that field inventory has identified specific landslides although these identified landslides are too small to be readily identified on orthophotos.

An accurate inventory of landsliding in the project area would take many weeks of field inventory. Photo inventory alone would miss too many landslides, especially road cut and fill slides, which probably make up the majority of landslide sedimentation in the project area. Instead we modeled landsliding based on geologic type and disturbance history and come up with a reasonable estimate of landsliding. We also factored in future wildfire based burn severity mapping. We did not devote time to mining effects as, to our knowledge, it has not been demonstrated that mining has had a significant impact on sedimentation in the project area.

G.2 Methodology and Data Used in Analysis

G.2.1 Datasets

<u>NHD</u> – National Hydrologic Dataset for the Mokelumne River sub-basin includes streams and lakes as well as man-made features such as reservoirs and pipelines.

<u>WBD_HU10</u> – Watershed Boundary Dataset, 10 digit (5th field) Hydrologic Units (watersheds). The North Fork Mokelumne River consists of two 5th field units, Upper North Fork Mokelumne River (HU code 1804001201) and Lower North Fork Mokelumne River (HU code 1804001204).

The split between Upper and Lower is at the confluence of North Fork Mokelumne River and Cole Creek, about 3 kilometers downstream of Salt Springs Reservoir, with Cole Creek considered in the Upper North Fork Mokelumne River watershed.

WBD_HU12 – Watershed Boundary Dataset, 12 digit (6th field) Hydrologic Units (sub-watersheds).

Project Boundary – The project boundary for this project was created using WBD_HU12. As the intent of the project is to determine a coarse sediment budget in the North Fork Mokelumne River watershed between Salt Springs Reservoir and Tiger Creek Afterbay, the entire North Fork Mokelumne River was not analyzed. Sixth field sub-watershed boundaries were used with the following exceptions. Watershed lines were drawn at the dam for Salt Springs Reservoir (to exclude the portion above the dam), at the dam for the Lower Bear River Reservoir (to exclude the portion above the dam), and at the dam for Tiger Creek Afterbay (to exclude the portion below the dam) to create a project boundary. The sub-watersheds in the project are as follows (See Table G.1).

Table G.1: Subwatersheds and acreage

Sub-watershed	*Sub-watershed Name*	*Project Hectares*	*Total Sub-watershed Hectares*
180400120105	Cole Creek	6,086	6,086
180400120106	Salt Springs Reservoir-North Fork Mokelumne River	648	11,325
180400120401	Bear River	3,968	13,629
180400120402	Blue Creek	7,504	7,504
180400120403	Panther Creek	4,852	4,852
180400120404	Tiger Creek-North Fork Mokelumne River	12,616	12,616
180400120405	Mill Creek-North Fork Mokelumne River	3,287	7,346
	Total Project Hectares	*38,961*	

Table G.2: Ownership for the project area and total acreage:

Owner/Manager	*Hectares*
Eldorado National Forest	13,473
Stanislaus National Forest	8,512
Bureau of Land Management	274
Private Land	16,702
Total Project Area	*38,961*

Roads – The roads for the project area have been pulled from the roads layers from the Eldorado and Stanislaus National Forests, with some additional roads added if readily visible on aerial imagery but not in either layer. A number of roads in the far western portion of the project area, in what appears to be a residential subdivision, have not yet been mapped. Most roads within the clip boundary had been attributed with "system" (county road, National Forest System Road, etc.), surface type, and lanes (indicator of road width). Unattributed roads I called Forest non-system or private (depending of land ownership) with single lane and native surface.

Table G.3: Road mileage summary for the project area

System	*Surface Type*	*Lanes*	*Miles*
State Highway	AC - ASPHALT	2 - DOUBLE LANE	15.2
County Road	AC - ASPHALT	2 - DOUBLE LANE	2.2
County Road	AGG - CRUSHED AGGREGATE OR GRAVEL	1 - SINGLE LANE	0.5
County Road	NAT - NATIVE MATERIAL	1 - SINGLE LANE	0.4
National Forest System Road	AC - ASPHALT	2 - DOUBLE LANE	1.7
National Forest System Road	AC - ASPHALT	1 - SINGLE LANE	4.4
National Forest System Road	BST - BITUMINOUS SURFACE TREATMENT	2 - DOUBLE LANE	8.6
National Forest System Road	BST - BITUMINOUS SURFACE TREATMENT	1 - SINGLE LANE	41.1
National Forest System Road	AGG - CRUSHED AGGREGATE OR GRAVEL	1 - SINGLE LANE	45.9
National Forest System Road	IMP - IMPROVED NATIVE MATERIAL	1 - SINGLE LANE	1.1
National Forest System Road	NAT - NATIVE MATERIAL	1 - SINGLE LANE	255.4
Forest Non-System Road	NAT - NATIVE MATERIAL	1 - SINGLE LANE	21.4
Private Road	AC - ASPHALT	1 - SINGLE LANE	0.1
Private Road	AGG - CRUSHED AGGREGATE OR GRAVEL	1 - SINGLE LANE	1.3
Private Road	NAT - NATIVE MATERIAL	1 - SINGLE LANE	228.5

Burn Severity and Fire History – These layers help show erosion-accelerating disturbances in the watershed. Fire history is not particularly useful since there is no indication of severity as there is in the burn severity layer; however burn severity layers only date from 1991 and younger.

Units – Timber harvest units on National Forest lands from the FACTS database, although we have included only land disturbing activities, not other activities tracked in the database such as stand inventories.

Timber Harvest Plans – State managed logging activity data on private land. Includes separate feature classes for Amador and Calaveras counties.

Digital Elevation Model – Grid of elevations, from which can be derived slope classes, contours, and hillshade.

Rainfall_Rantz – Average rainfall.

Aerial Imagery – Many tiles of rectified aerial imagery (orthophotos), pulled from public access internet sites, mostly dating around 2010.

Soils_geo_group – This is a feature class compiled from the best available bedrock mapping and Order 2 soil surveys. Individually, the three Order 2 soil surveys and the bedrock mapping do not cover the entire project area, and the soil surveys (three of them) across the area do not cover the entire project area. The bedrock mapping and soil surveys were combined to make one feature class that covered the project area. . This feature class includes the original map unit symbols and map unit names from the soil surveys, the geologic groups from the bedrock mapping, and the attribute soils_geo_group with surface texture and percent fines interpretations for each group. The soils_geo_group, with interpretations, are as follows (See Appendix C: C.3.2.4).

Table G.4: Soil Layer Descriptions

Soils Geo Group	*Percent Fines*	*Surface Texture*
Deep to moderately deep soils, granitic	30%	coarse sandy loam
Glacial deposits, mostly granitic	30%	coarse sandy loam
Rock outcrop with deep pockets of soil, mostly granitic	30%	coarse sandy loam
Rock outcrop, mostly granitic	30%	coarse sandy loam
Shallow to moderately deep soils, volcanic	40%	cobbly sandy loam
Deep to moderately deep soils, volcanic	40%	gravelly sandy loam
Marshy ground, mostly granitic	40%	sandy loam
Shallow to moderately deep soils, metamorphic	50%	gravelly loam
Deep soils, metamorphic	60%	loam

G.3 Methods

Order 2 soil mapping is of higher resolution than bedrock mapping, so soil mapping lines are used instead of bedrock lines for the soils_geo_group. In cases where soil surveys are not edge matched correctly, or soil survey information is not available, the bedrock interpretation was used to determine soils_geo_group value. Rock outcrop, glacial deposits, and marshy ground could occur on any bedrock type, and the soil survey information does not specify bedrock type for these geologic groups. The majorities of these types are in granitic bedrock and acquires a granitic interpretation for soil texture and percent fines.

There are three basic rock types in the project area: granitic, volcanic, and metamorphic. Granitic rocks are those of the Sierra Nevada batholith, mostly granodiorite or diorite. When exposed as rock outcrop these are nearly impervious to landsliding and erosion, except for rock falls and small amounts of sheet erosion as individual grains weather and wash from exposed bedrock. But once weathered to soil, erosion can occur readily, especially after disturbance, because of coarse textured soils with low percentages of binding fine material. Volcanic rock types are primarily andesitic mudflow deposits often identified as the Mehrten formation. The Mehrten formation is generally identified as the most landslide-prone group of rocks in the Sierra Nevada area. Even when exposed as rock outcrop, the andesitic mudflow deposits are generally weak and fractured and subject to landsliding. The metamorphic rocks include metasediments and metavolcanics of the

Northern Sierra terrane, generally the most weathered but least erosion-prone of the bedrock types.

Interpretations were made for percent_fines for each soils_geo_group based on dominant surface texture and bedrock type for each soil map unit. This interpretation is designed to allow estimation of eroded material that would likely be trapped in a reservoir. The majority of finer material, less than 63 microns, would likely wash through a reservoir while the majority of coarser material, greater than 63 microns, would likely be held in a reservoir and contribute to reservoir filling.

G.4 Results

A model estimating sediment delivery to streams from mass wasting was modified for the project area. This model has its empirical base in the Salmon Sub-basin Sediment Analysis [de la Fuente & Haessig, 1994] and uses methodology developed in Amaranthus et al. [1985], the Grider EIS [USFS, 1989] and KNF LRMP [USFS, 1995]. The model estimates sediment delivery using a matrix of coefficients (see Table G.5 below). Sediment delivery coefficients derived for this analysis are based on the Klamath Mountains work, although there is not much consistency between the North Fork Mokelumne project area and the Klamath Mountains. For one thing, landsliding rates are much higher in the Klamath Mountains than the Sierra Nevada. Table G.1 displays values to correlate mapped geology and soils types for the project area with mass wasting rates from the Klamath Mountains. End-result total sediment production estimates will be high compared to actual sediment production, but relative mass production between background, roads, and other disturbance (wildfire and timber harvest) should be realistic.

The project area for this analysis consists of the watershed area draining to Tiger Creek Afterbay, excluding the areas above Salt Springs Reservoir and Lower Bear River Reservoir. Total project area is 96,276 acres. Geology and soils types are mapped for the project area, as are roads and other disturbances. Roads and other disturbances are intersected with geology in GIS and acreages of each type of intersection is computed and multiplied by the factors in Table G.5 to arrive at the estimated mass wasting values displayed in Table G.6.

Table G.5: Estimated sediment delivery in m³/hectare/decade

Geology Type Description	*Slope Class*	*Background (estimate assuming area is undisturbed)*	*Roads*	*High impact fire or harvest[1]*	*Moderate impact fire or harvest[2]*
deep soils, metamorphic	<40%	0.5	34	3.9	2.2
deep soils, metamorphic	>40%	2.3	154.9	4.7	3.5
deep to moderately deep soils, granitic	<40%	1	66.1	10.4	5.7
deep to moderately deep soils, granitic	>40%	1.9	1105.2	19.6	10.7
deep to moderately deep soils, volcanic	<40%	2.3	154.9	4.7	3.5
deep to moderately deep soils, volcanic	>40%	3.6	292.8	11.2	7.4
glacial deposits, mostly granitic	<40%	1	66.1	10.4	5.7
glacial deposits, mostly granitic	>40%	4.1	12.1	10.4	7.3
marshy ground, mostly granitic	<40%	1	66.1	10.4	5.7
marshy ground, mostly granitic	>40%	4.1	12.1	10.4	7.3
rock outcrop with deep pockets of soil, mostly granitic	<40%	0.1	0.9	0.5	0.3
rock outcrop with deep pockets of soil, mostly granitic	>40%	1	66.1	10.4	5.7
rock outcrop, mostly granitic	<40%	0	0.2	0.1	0.1
rock outcrop, mostly granitic	>40%	0.1	0.9	0.5	0.3
shallow to moderately deep soils, metamorphic	<40%	0.1	0.9	0.5	0.3
shallow to moderately deep soils, metamorphic	>40%	0.5	34	3.9	2.2
shallow to moderately deep soils, volcanic	<40%	0.5	34	3.9	2.2
shallow to moderately deep soils, volcanic	>40%	2.3	154.9	4.7	3.5

[1] Includes clear cuts and other equivalent silvicultural prescriptions and wildfire resulting in canopy removal of 80 percent or more.

[2] Includes partial cuts and wildfire resulting in canopy removal of between 30 and 80 percent.

Table G.6: Estimated Sediment Delivery for the North Fork Mokelumne River

Background	*Additional from Roads*	*Additional from Harvest and Wildfire pre-2002*	*Total 2002*	*Additional from Wildfire and Harvest post-2007*	*Total 2007*
51,272	54,859	12,337	118,468	29,097	147,565

Predicted sedimentation volumes are in cubic meters that may be generated in a flood event with recurrence interval of 10-20 years. “Background” is the expectation if the project area is undeveloped, without roads, wildfire, or harvest units.

Time frames of 2002 and 2007 are selected for this analysis to demonstrate the impacts of the Power Fire of 2004 and other wildfires that occurred in 2002 and 2003. The 2007 year is used as the post-wildfire output because salvage harvest operations from the Power Fire were still ongoing in 2006. As displayed in Table 6, the Power Fire, along with other wildfires and salvage operations during that time period, is expected to increase mass wasting sedimentation considerably, though not nearly as much as the chronic conditions that results from the extensive road network within the project area.

Other Considerations – Forest data concerning mining activity was not obtained, but there appears to be (based on review of orthophotos) very little stream sedimentation that has occurred in the project area as a result of mining.

G.5 Tiger Creek Afterbay

Tiger Creek Afterbay capacity at the time it was built (1931) was 4,884,588 cubic meters (3960 acre-feet), based on the info historical data. A bathymetric survey of the Afterbay was performed in the fall of 2013 (Appendix F), resulting in an estimated 2013 capacity of 1,158,974 cubic meters (940 acre-feet). Therefore, the amount of sediment deposition over 82 years, not including an unknown quantity of sediment flushed through the Afterbay dam, is 3,725,614 cubic meters (3020 acre-feet). In this analysis, we estimate an average non-fire (background + road erosion) mass-wasting sediment production of about 106,069 cubic meters (86 acre-feet) per year. For the North Fork Mokelumne study area of 38,978 ha, this is equivalent to a sediment yield of 2.72 cubic meters per hectare per year, or about 4 Mg/ha/yr. As previously noted, this estimate is on the high side because it uses coefficients developed for the more erodible Klamath terrain. Using our average of 106,069 cubic meters per year, it would take only 35 years for the Afterbay to collect the amount of sediment deposited in it, rather than the actual 82 years it took. This confirms that the average non-fire sediment production rate from the sediment budget report is higher than actual sediment production (assuming that sediment flushing is small relative to total deposition), although not out of the range of observed sediment production rates in the Sierra Nevada. As noted in this chapter, the relative importance of background, roads, fire, and harvest-related erosion is more reliable and relevant to management decisions than the magnitude of the estimates.

References:

Amaranthus, Michael P., Raymond M. Rice, Nicholas R. Barr, and Robert Ziemer, 1985, *Logging and Forest Roads Related to Increased Debris Slides in Southwest Oregon*: Journal of Forestry, v. 83, no. 4, p. 229-233.

de la Fuente, Juan & Polly Haessig, 1994, *Salmon Sub-basin Sediment Analysis*: USDA Forest Service, Klamath National Forest, Yreka, CA.

USDA Forest Service (USFS), 1989, *Grider Fire Recovery Project, Final Environmental Impact Statement*: USDA Forest Service, Klamath National Forest, Yreka, CA.

USDA Forest Service (USFS), 1995, *Record of Decision for the Final Environmental Impact Statement for the Klamath National Forest*: USDA Forest Service, Klamath National Forest, Yreka, CA

Appendix H: Bibliography on Wildfire, Fuels Reduction Treatment, and Prescribed Fire Effects on Runoff and Erosion

H.1 Wildfire effects on hillslope runoff and erosion

H.1.1 Badia, D., and Marti, C., 2008, Fire and rainfall energy effects on soil erosion and runoff generation in semi-arid forested lands: Arid Land Research and Management 22:93-108.

http://frames.nacse.org/ttrs/22000/22651.html

A study of artificial wildfire effects was conducted using sprinkler experiments in a semiarid forest in Spain. Only the litter layer was burned. Sediment yield increased between by factors ranging from 18.5 to 33.6 after wildfire. Runoff increased by a factor of 1.6 after wildfire owing to reduced infiltration.

H.1.2 Carroll, E.M., Miller, W.W., Johnson, D.W., Saito, L., Qualls, R.G., and Walker,R.F., 2007, Spatial analysis of a large magnitude erosion event following a Sierran wildfire: Journal of Environmental Quality 36(4):1105-1111.

https://www.agronomy.org/publications/jeq/tocs/36/4

The 2002 Gondola Fire near Lake Tahoe was followed within two weeks by an intense rain and hail storm. Erosion from the burned area (8,900 to 10,000 g/square meter, or 1,800 to 6,700 g/square meter/mm rainfall) was more than 4 orders of magnitude larger than erosion rates reported in previous studies of wildfires. Most of the sediment and ash was deposited in a low-gradient riparian zone.

H.1.3 Lanini, J.S., Clark, E.A., and Lettenmaier, D.P., 2009, Effects of fire-precipitation timing and regime on post-fire sediment delivery in Pacific Northwest forests: Geophysical Research Letters, vol. 36, L01402, 5 pp.

http://www.agu.org/journals/gl/gl0901/2008GL034588/2008GL034588.pdf

Modeled sediment delivery for a forested watershed on the east slope of the Northern Cascades was about 10 times higher for high-severity fire than no fire.

Excerpt from Conclusions:

"Post-fire increases in sediment generation were primarily related to slope failures, and were strongly controlled by the interactions of post-fire loss of root cohesion with spring snowmelt. Spring snowmelt changes in turn were closely linked to reduction in overstory LAI, which reduced winter ablation and hence increased spring snow accumulation, and increased peak spring melt rates due to reduction in canopy attenuation of solar radiation.

High sediment generation was critically dependent on interactions of high snow accumulation years during the period when post-fire root cohesion was at its lowest."

H.1.4 Mayor, A.G., Bautista, S., Llovet, J., and Bellot, J., 2007, Post-fire hydrological and erosional responses of a Mediterranean landscape: Seven years of catchment-scale dynamics: Catena 71: 68-75.

http://frames.nacse.org/ttrs/22000/22482.html

Runoff was 35 mm in burned catchment, 0.03 mm in unburned. Sediment yield was 4,563 kg/ha in burned catchment, 0.12 kg/ha in unburned. Effects of fire persisted at least 5 years.

Excerpt from abstract:

"We studied medium-term dynamics of fire effects on catchment runoff and sediment yield in a dry-Mediterranean area in Alicante, E Spain. The study area was a mixed forest and agricultural terraced landscape that was affected by a wildfire in August 1998. We measured runoff and sediment yield in two catchments – burned and unburned – during the first seven years after the wildfire. Post-fire vegetation cover dynamics were also monitored. Total runoff and sediment yield in the burned catchment (35 mm and 4563 kg ha-1, respectively) were considerably greater than in the unburned catchment (0.03 mm, and 0.12 kg ha-1). Annual runoff and sediment yield increased with time after fire until the third post-fire year, and then decreased progressively. However, even five years after the wildfire, differences in annual runoff and sediment yield between the burned and the unburned catchments were still about two orders of magnitude. Post-fire vegetation cover increased very slowly during the initial post-fire years, and differences between burned and unburned areas persisted six years after the wildfire. Most studies on post-fire hydrology and erosion have identified the first one or two post-fire years as the critical period for high runoff and erosion risk, indicating short-term ecosystem resilience to wildfire. However, we found that wildfire impact on catchment runoff and sediment yield in Mediterranean drylands may be amplified by drought periods that delay plant recovery, and thus wildfire impacts may be still of great importance several years after the fire."

H.1.5 Miller, M.A., MacDonald, L.H., Robichaud, P.R., and Elliot, W.J., 2011, Predicting post-fire hillslope erosion in forests lands of the western United States: International Journal of Wildland Fire 2001, 20: 982-999

http://www.publish.csiro.au/?act=view_file&file_id=WF09142.pdf

Abstract:

"Many forests and their associated water resources are at increasing risk from large and severe wildfires due to high fuel accumulations and climate change. Extensive fuel treatments are being proposed, but it is not clear where such treatments should be focused.

The goals of this project were to: (1) predict potential post-fire erosion rates for forests and shrublands in the western United States to help prioritize fuel treatments; and (2) assess model sensitivity and accuracy. Post-fire ground cover was predicted using historical fire weather data and the First Order Fire Effects Model. Parameter files from the Disturbed Water Erosion Prediction Project (WEPP) were combined with GeoWEPP to predict post-fire erosion at the hillslope scale. Predicted median annual erosion rates were 0.1–2Mg/ha/year for most of the intermountain west,10–40Mg/ha/year for wetter areas along the Pacific Coast and up to 100Mg/ha/year for north-western California. Sensitivity analyses showed the predicted erosion rates were predominantly controlled by the amount of precipitation rather than surface cover. The limited validation dataset showed a reasonable correlation between predicted and measured erosion rates (*R*-squared = 0.61), although predictions were much less than measured values. Our results demonstrate the feasibility of predicting post-fire erosion rates on a large scale. The validation and sensitivity analysis indicated that the predictions are most useful for prioritizing fuel reduction treatments on a local rather than interregional scale, and they also helped identify model improvements and research needs.

H.1.6 Moody, J.A., and Martin, D.A., 2004, Wildfire impacts on reservoir sedimentation in the western United States: Proceedings of the Ninth International Symposium on River Sedimentation, October 18-21, 2004, Yichang, China, p. 1095-1102

http://wwwbrr.cr.usgs.gov/projects/Burned_Watersheds/Files/fire_reservoir_sedimentati o n.pdf

Potential for postfire sediment deposition in reservoirs was found to be related more strongly to fire frequency, soil erodibility, channel slope, and rainfall intensity than to tectonic setting and underlying bedrock geology. Potential reservoir sedimentation rates were estimated to be high both for the tectonically active Coast and Transverse Ranges and the relatively stable Sierra Nevada.

H.1.7 Moody, J.A., Martin, D.A., Haire, S.L., and Kinner, D.A., 2008, Linking runoff response to burn severity after a wildfire: Hydrological Processes 22: 2063-2074.

http://water.usgs.gov/nrp/proj.bib/Publications/2008/moody_martin_etal_2008.pdf

Fire effects on runoff/rainfall ratio depends on spatial distribution of burn severity, near-channel areas exert more influence than ridge areas.

H.1.8 Pierson, F.B., Robichaud, P.R., Moffet, C.A., Spaeth, K.E., Hardegree, S.P., Clark, P.E., and Williams, C.J., 2008, Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape: Hydrological Processes 22: 2916-2929.

http://ddr.nal.usda.gov/bitstream/10113/31594/1/IND44082838.pdf

Burned area 3-year cumulative runoff in northwestern Nevada was 298 L vs. 16 L on unburned control. Burned area 3-year cumulative sediment yield was 20,400 g/sq m vs. 6

g/sq m on unburned control. Fire effects were still evident, though reduced, 3 years postfire.

Excerpts from abstract:

"The greatest impact of fire was on the dynamics of runoff once overland flow began. Reduced ground cover on burned hillslopes allowed overland flow to concentrate into rills. The 3-year cumulative runoff from concentrated flow simulations on burned hillslopes (298 l) was nearly 20 times that measured on unburned hillslopes (16 l). The 3-year cumulative sediment yield from concentrated flow on burned and unburned hillslopes was 20,400 g/square meter and 6 g/square meter respectively. Fire effects on runoff generation and sediment were greatly reduced, but remained, 3 years post-fire. The results indicate that the impacts of fire on runoff and erosion from severely burned steep sagebrush landscapes vary significantly by microsite and process, exhibiting seasonal fluctuation in degree, and that fire-induced increases in runoff and erosion may require more than 3 years to return to background levels."

H.1.9 Reneau, S.L., Katzman, D., Kuyumjian, G.A., Lavine, A., and Malmon, D.V., 2007, Sediment delivery after a wildfire: Geology 35(2): 151-154.

http://geology.gsapubs.org/content/35/2/151.full.pdf+html

In the first year following the Cerro Grande Fire in New Mexico, sediment delivery to a downstream reservoir was 140 times larger than pre-fire delivery. Delivery of ash and fine-grained sediment to the reservoir peaked within a year of the fire, while transport of coarser sediment did not approach pre-fire levels until the 5th year after the fire.

H.1.10 Rulli, M.C., and Rosso, R., 2007, Hydrologic response of upland catchments to wildfires: Advances in Water Resources 30(10): 2072-2086.

[not available via internet]

Probability of flooding can increase by a factor of 10 in first year after fire.

H.1.11 Smith, H.G., Sheridan, G.J., Lane, P.N.J., Nyman, P., Haydon, S., 2011, Wildfire effects on water quality in forest catchments: A review with implications for water supply, Journal of Hydrology, Volume 396, Issues 1–2, 5 January 2011, Pages 170-192.

http://www.sciencedirect.com/science/article/pii/S0022169410006748

Reviews wildfire effects on sediment and dissolved constituents.

H.2 Wildfire effects on landslides and channel erosion and deposition

H.2.1 Benda, L., Miller, D., Bigelow, P., and Andras, D., 2003, Effects of post-wildfire erosion on channel environments, Boise River, Idaho: Forest Ecology and Management 178(2003):105-119.

http://www.sierraforestlegacy.org/Resources/Conservation/FireForestEcology/FireScienceResearch/Post-fireEffects/Postfire-Benda03.pdf

Sediment eroded from burned forests in Idaho resulted in substantial changes to the morphology of major river channels. An increase in sediment supply resulting from wildfire followed by rainstorms aggraded an entire 4th order valley floor and rejuventated alluvial fans at tributary confluences.

H.2.2 Canfield, H.E., Wilson, C.J., Lane, L.J., Crowell, K.J., and Thomas, W.A., 2005, Modeling scour and deposition in ephemeral channels under climate change; rates, implications, and feedback: Catena Giessen 61(2-3):273-291.

http://www.mendeley.com/research/modeling-scour-deposition-ephemeral-channels-after-wildfire-soil-erosion-under-climate-change-rates-implications-feedbacks/

The HEC6T model was successfully used to model sediment erosion and deposition in ephemeral channels following fires in Arizona.

H.2.3 Cannon, S. H., 2001, Debris-flow generation from recently burned watersheds: Environmental & Engineering Geoscience 7(4): 321-341.

http://pubs.er.usgs.gov/publication/70022812

Evaluation of the erosional response of 95 recently burned drainage basins in Colorado, New Mexico and southern California to storm rainfall provides information on the conditions that result in fire-related debris flows. Debris flows were produced from only 37 of 95 (similar to 40 percent) basins examined; the remaining basins produced either sediment-laden streamflow or no discernable response. Debris flows were thus not the prevalent response of the burned basins. The debris flows that did occur were most frequently the initial response to significant rainfall events. Although some hillslopes continued to erode and supply material to channels in response to subsequent rainfall events, debris flows were produced from only one burned basin following the initial erosive event. Within individual basins, debris flows initiated through both runoff and infiltration-triggered processes. The fact that not all burned basins produced debris flows suggests that specific geologic and geomorphic conditions may control the generation of fire-related debris flows. The factors that best distinguish between debris-flow producing drainages and those that produced sediment-laden streamflow are drainage-basin morphology and lithology, and the presence or absence of water-repellent soils. Basins underlain by sedimentary rocks were most likely to produce debris flows that contain large material, and sand- and gravel-dominated flows were generated primarily from terrain underlain by decomposed granite. Basin-area and relief thresholds define the morphologic conditions under which both types of debris flows occur. Debris flows containing large material are more likely to be produced from basins without water- repellent soils than from basins with water repellency. The occurrence of sand-and gravel-dominated debris flows depends on the presence of water-repellent soils.

H.2.4 Cannon, S. H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., and Parrett, C., 2009, Predicting the probability and volume of postwildfire debris flows in the intermountain western United States: Geological Society of America Bulletin 122(1-2): 127-144.

http://gsabulletin.gsapubs.org/content/early/2009/09/24/B26459.1.full.pdf+html

Empirical models to estimate the probability of occurrence and volume of post-wildfire debris flows can be quickly implemented in a geographic information system (GIS) to generate debris-flow hazard maps either before or immediately following wildfires. Models that can be used to calculate the probability of debris-flow production from individual drainage basins in response to a given storm were developed using logistic regression analyses of a database from 388 basins located in 15 burned areas located throughout the U.S. Intermountain West. The models describe debris-flow probability as a function of readily obtained measures of areal burned extent, soil properties, basin morphology, and rainfall from short-duration and low-recurrence-interval convective rainstorms. A model for estimating the volume of material that may issue from a basin mouth in response to a given storm was developed using multiple linear regression analysis of a database from 56 basins burned by eight fires. This model describes debris- How volume as a function of the basin gradient, aerial burned extent, and storm rainfall. Applications of a probability model and the volume model for hazard assessments are illustrated using information from the 2003 Hot Creek fire in central Idaho. The predictive strength of the approach in this setting is evaluated using information on the response of this fire to a localized thunderstorm in August 2003. The mapping approach presented here identifies those basins that are most prone to the largest debris-flow events and thus provides information necessary to prioritize areas for postfire erosion mitigation, warnings, and prefire management efforts throughout the Intermountain West.

H.2.5 Cannon, S.H., and Gartner, J.E, 2005, Wildfire-related debris flow from a hazard perspective: Chapter 15 in: Jakob, M., and Hungr, O. (eds.), Debris flow hazards and related phenomena, Praxis Springer, no pagination.

http://landslides.usgs.gov/docs/cannon/Cannon_Gartner_Springer_2005.pdf

This chapter provides an overview of debris-flow hazards related to wildfires in the mountainous areas of the western United States. Information on peak flows, frequencies, and size of flows is summarized.

H.2.6 Carroll, E. M., Miller,W.W., Johnson, D.W., Saito, L., Qualls, R.G., and Walker, R.F., 2007, Spatial analysis of a large magnitude erosion event following a Sierran wildfire: Journal of Environmental Quality 36(4): 1105-1111.

http://frames.nacse.org/ttrs/22000/22323.html

High intensity wildfire due to long-term fire suppression and heavy fuels buildup can render watersheds highly susceptible to wind and water erosion. The 2002 "Gondola" wildfire, located just southeast of Lake Tahoe, NV-CA, was followed 2 weeks later by a severe hail and rainfall event that deposited 7.6 to 15.2 mm of precipitation over a 3 to 5 hour time period. This resulted in a substantial upland ash and sediment flow with subsequent down-gradient riparian zone deposition. Point measurements and ESRI ArcView were applied to spatially assess source area contributions and the extent of ash and sediment flow deposition in the riparian zone. A deposition mass of 380 Mg of ash and sediment over 0.82 ha and pre-wildfire surface bulk density measurements were used in conjunction with two source area assessments to generate an estimation of 10.1 mm as the average depth of surface material eroded from the upland source area. Compared to previous measurements of erosion during rainfall simulation studies, the erosion of 1800 to 6700 g m(-2) mm(-1) determined from this study was as much as four orders of magnitude larger. Wildfire, followed by the single event documented in this investigation, enhanced soil water repellency and contributed 17 to 67% of the reported 15 to 60 mm per 1,000 years of non-glacial, baseline erosion rates occurring in mountainous, granitic terrain sites in the Sierra Nevada. High fuel loads now common to the Lake Tahoe Basin increase the risk that similar erosion events will become more commonplace, potentially contributing to the accelerated degradation of Lake Tahoe's water clarity.

H.2.7 Gartner, J. E., Cannon, S.H., Santi, P.M., and DeWolfe, V.G., 2008, Empirical models to predict the volumes of debris flows generated by recently burned basins in the western US: Geomorphology 96(3-4): 339-354.

http://www.journals.elsevier.com/geomorphology/

Recently burned basins frequently produce debris flows in response to moderate-to- severe rainfall. Post-fire hazard assessments of debris flows are most useful when they predict the volume of material that may flow out of a burned basin. This study develops a set of empirically-based models that predict potential volumes of wildfire-related debris flows in different regions and geologic settings. The models were developed using data from 53 recently burned basins in Colorado, Utah and California. The volumes of debris flows in these basins were determined by either measuring the volume of material eroded from the channels, or by estimating the amount of material removed from debris retention basins. For each basin, independent variables thought to affect the volume of the debris flow were determined. These variables include measures of basin morphology, basin areas burned at different severities, soil material properties, rock type, and rainfall amounts and intensities for storms triggering debris flows. Using these data, multiple regression analyses were used to create separate predictive models for volumes of debris flows generated by burned basins in six separate regions or settings, including the western U.S., southern California, the Rocky Mountain region, and basins underlain by sedimentary, metamorphic and granitic rocks. An evaluation of these models indicated that the best model (the Western U.S. model) explains 83% of the variability in the volumes of the debris flows, and includes variables that describe the basin area with slopes greater than or equal to 30%, the basin area burned at moderate and high severity, and total storm rainfall. This model was independently validated by comparing volumes of debris flows reported in the literature, to volumes estimated using the model. Eighty- seven percent of the reported volumes were within two residual standard errors of the volumes predicted using the model. This model is an improvement over previous models in that it includes a measure of burn severity and an estimate of modeling errors. The application of this model, in conjunction with models for the probability of debris flows, will enable more complete and rapid assessments of debris flow hazards following wildfire.

H.2.8 DeGraff, J., Wagner, D., Gallegos, A., DeRose, M., Shannon, C., and Ellsworth, T., 2011, The remarkable occurrence of large rainfall-induced debris flows at two different locations on July 12, 2008, Southern Sierra Nevada, CA, USA: Landslides 8(2011):343- 353.

http://www.springerlink.com/content/f88568301m244650/fulltext.pdf

Two very large debris flows in the southern Sierra Nevada occurred on July 12, 2008, on recently-burned watersheds. Wildfire appears to have been a factor in at least one of the debris flows.

H.3 Wildfire effects on in-stream woody debris

H.3.1 Berg, N.H., Azuma, D., and Carlson, A., 2002, Effects of wildfire on in-channel woody debris in the Eastern Sierra Nevada, California: USDA Forest Service General Technical Report GTR-181, p. 49-63

Recruitment of large woody debris was higher in a burned watershed relative with an unburned control watershed within one year of a fire in the eastern Sierra Nevada. However, the burned watershed produced fewer debris jams owing to the generally smaller size of the remaining debris.

http://www.fs.fed.us/psw/publications/documents/gtr-181/006_Berg.pdf

H.3.2 Bragg, D.C., 2000, Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system: Ecology 81(5):1383-1394.

Catastrophic events such as wildfires increased the amount of large woody debris in small streams in Utah.

http://www.esajournals.org/doi/abs/10.1890/0012-9658(2000)081%5B1383:SCAILW%5D2.0.CO%3B2

H.4 Fuels treatment effects on hillslope runoff and erosion

H.4.1 Benavides-Solorio, J., and MacDonald, L.H., 2001, Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range: Hydrological Processes 15(15):2931-2952.

http://warnercnr.colostate.edu/~leemac/publications/PostFireRunoff_ErosionFromSimula tedRainfallonSmallPlotsColoradoFrontRange.pdf

Runoff increased only by 15-30%. Sediment yields from recent high-severity fires were 10 to 26 times higher than yields from unburned and low severity areas. Sediment yields from older high-severity burns about the same as unburned areas.

Abstract:

“Wildfires in the Colorado Front Range can trigger dramatic increases in runoff and erosion. A better understanding of the causes of these increases is needed to predict the effects of future wildfires, estimate runoff and erosion risks from prescribed fires, and design effective post-/ire rehabilitation treatments. The objective of this project was to determine whether runoff and sediment yields were significantly related to the site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. To eliminate the variability due to natural rainfall events, we applied an artificial storm of approximately 80 mm h-1 on 26 I m2 plots in the summer and fall of 2000. The plots were distributed among a June 2000 wildfire, a November 1999 prescribed fire, and a July 1994 wildfire. For 23 of the 26 plots the ratio of runoff to rainfall exceeded 50%. Nearly all sites exhibited strong natural or fire-induced water repellency, so the runoff ratios were only 15-30% larger for the high-severity plots in the two more recent fires than for the unburned or low-severity plots. The two high-severity plots in the 1994 wildfire had very low runoff ratios, and this probably was due to the high soil moisture conditions at the time of the simulated rainfall and the resulting reduction in the natural water repellency. Sediment yields from the high-severity sites in the two more recent fires were 10-26 times greater than the unburned and low-severity plots. The plots burned at high severity in 1994 yielded only slightly more sediment than the unburned plots. Percent ground cover explained 81 % of the variability in sediment yields, and the sediment yields from the plots in the 1994 wildfire are consistent with the observed recovery in percent ground cover.”

H.4.2 Benavides-Solorio, J.D., 2003, Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range: Ph.D. Dissertation, Department of Earth Resources, Colorado State University, Fort Collins, Colorado.

http://frames.nacse.org/6000/6366.html

This study evaluated plot and hillslope scale effects of prescribed fires and wildfires. Effects on runoff were minor. High burn severity plots had increases of 16 to 33 times background sediment yields. High-severity wildfire sediment yield was 10 Mg/ha/yr. High-severity prescribed fire sediment yield was 0.1 to 4 Mg/ha/yr.

H.4.3 Berg, N.H., and Azuma, D.L., 2010, Bare soil and rill formation following wildfires, fuel reduction treatments, and pine plantations in the Southern Sierra Nevada, USA: International Journal of Wildland Fire 2010: 478-489.

http://www.publish.csiro.au/?act=view_file&file_id=WF07169.pdf

A plot study of wildfire and fuels treatments effect on rill and bare soil formation showed that wildfires increase both rilling and bare soil, but differences between burned and undisturbed reference plots disappear after 4 to 6 years. Rill formation on plots affected by fuels reduction treatments was minimal, and bare soil on plots within fuels treatments did not differ significantly from reference plots.

H.4.4 Cram, D.S., Baker, T.T., Fernald, A.G., Madrid, A., and Rummer, B., 2007, Mechanical thinning impacts on runoff, infiltration, and sediment yield following fuel reduction treatments in a southwestern dry mixed conifer forest: Journal of Soil and Water Conservation 62(5):359-366.

http://frames.nacse.org/ttrs/22000/22338.html

Heavy mechanical use on steep slopes resulted in fourfold increase in runoff and an increase in sediment yield by factor of 22.

Excerpt: "Significantly, the results of this study indicated light to moderate disturbance from mechanical operations did not significantly increase erosion over undisturbed control areas, even on steeper slopes."

H.4.5 Elliot, W.J., 2010, Effects of forest biomass use on watershed processes in the Western United States: Western Journal of Applied Forestry 25(1):12-17.

http://ddr.nal.usda.gov/bitstream/10113/38922/1/IND44322342.pdf

Biomass removal can result in soil compaction and increased surface runoff on forested hillslopes. Implementation of appropriate Best Management Practices can mitigate these effects. Biomass removal can reduce erosion risks associated with wildfires.

H.4.6 Hatchett, B., Hogan, M.P., and Grismer, M.E., 2006, Mechanical mastication thins Lake Tahoe forest with few adverse impacts: California Agriculture 60(2): 77-82.

http://ucanr.org/repository/cao/landingpage.cfm?article=ca.v060n02p77&fulltext=yes

Mastication had little effect on soil compaction or erosion at an experimental site on the west shore of Lake Tahoe.

H.4.7 Johansen, M.P., Hakonson, T.E., and Breshears, D.D., 2001, Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands: Hydrological Processes 15:2953-2965.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.384/pdf

Runoff from plots burned in a Ponderosa pine forest during the Cerro Grande Fire in New Mexico increased by a factor of 2. Sediment yield increased by a factor of 25.

H.4.8 Loupe, T.M., Miller, W.W., Johnson, D.W., Sedinger, J.S., Carroll, E.M., Walker, R.F., Murphy, J.D., and Stein, C.M., 2009, Effects of mechanical harvest plus chipping and prescribed fire on Sierran runoff water quality: Journal of Environmental Quality 38(2):537-547.

https://www.agronomy.org/publications/jeq/tocs/38/2

Mechanical (CTL) thinning, chipping, and prescribed fire had minimal effects on nutrient concentrations in post-treatment runoff.

H.4.9 Madrid, A., Fernald, A.G., Baker, T.T., and Vanleeuwen, D.M., 2006, Evaluation of silvicultural treatment effects on infiltration, runoff, sediment yield, and soil moisture in a mixed conifer New Mexico forest: Journal of Soil and Water Conservation 61(3):159-168.

http://www.jswconline.org/content/61/3/159.abstr
act

Partial thinning without burning in a New Mexico mixed-conifer forest did not significantly affect infiltration rates, runoff rates, or soil moisture. Sediment yield was very low in all cases.

Excerpt: "We conclude that southwestern mixed conifer forest may be partially thinned without risk of significant increases in hillslope runoff and sediment yield."

H.5 Fuels treatment effects on in-stream woody debris

H.5.1 Beche, L.A., Stephens, S.L., and Resh, V., 2005, Effects of prescribed fire on a Sierra Nevada (California, USA) stream and its riparian zone: Forest Ecology and Management 218(1-3): 37-59.

http://www.sciencedirect.com/science/article/pii/S0378112705004457

Prescribed fire had no effect on woody debris volume or recruitment.

H.5.2 Zelt, R.B., and Wohl, E.E., 2003, Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming: Geomorphology 57(3-4):217-233.

http://www.sciencedirect.com/science/article/pii/S0169555X03001041

Frequency of in-channel large woody debris was lower in a burned watershed than in an adjacent unburned control, but debris jams were more common in the burned watershed.

Appendix I: Bibliography on Hydrologic Effects of Meadow Restoration in the Sierra Nevada

I.1 Introduction

Meadow restoration has many potential benefits, including improved water quality, streamflow regimen, flood attenuation, aquatic and terrestrial habitats, aesthetics, and forage production, and reduction of forest fuels. Although most of these benefits enjoy wide public support, the effects of restoration on downstream surface flows remain controversial owing to the temporary retention and increased evapotranspiration of water in restored meadow aquifers.

Restoration of eroded wet meadows in the Sierra Nevada is a goal of the USDA Forest Service Pacific Southwest Region. The National Environmental Policy Act requires that the "best available science" be used to assess potential effects of proposed restoration projects on National Forests. This bibliography summarizes selected references that may be useful for analyzing the effects of proposed meadow restoration projects on downstream baseflows. It is intended to aid National Forest hydrologists on interdisciplinary teams charged with analyzing effects of alternative approaches to meadow restoration, and to provide background information for our ongoing meadow hydrology assessment in the Sierra Nevada.

This bibliography is divided into 9 major topics (A to I). Each major topic has a short introductory paragraph. Titles within each topic are listed alphabetically by author and numbered sequentially for ease of reference. For each publication, I have provided a web link and a brief summary of results relevant to effects of restoration on streamflow. Publications are listed under only a single major topic, but may have relevance for others as well. The topics most likely to be useful for meadow restoration NEPA are A through E, which are specific to mountain meadows in the western United States. Topics G through I deal with groundwater-surface water interactions from other geographic areas, and are primarily intended as supporting information for our ongoing meadow hydrology assessment.

This bibliography focuses on the issue of summer baseflows downstream of restored meadows. Although some of the references deal with related topics such as vegetation response and flood attenuation, I did not attempt to collect all, or even most, of the literature on these topics, or others such as the origins and chronology of meadows, causes of meadow erosion, effects of livestock grazing, or technical standards for restoration. If you would like additional information on these or other related topics, please contact me.

The available literature on most of the main topics is much more extensive than the studies summarized below. Topic A. is an exception—I have cited all published information I could find that is directly relevant to this topic.

I.2 Meadow restoration effects on groundwater storage and streamflow in the western United States

Most studies have demonstrated that restoration increases summer baseflows downstream of restored meadows. The studies have been primarily undertaken in the northern Sierra Nevada on large and relatively low-gradient meadows along tributaries of the Feather River.

I.2.1 Cornwell, Kevin, and Brown, Kamala, 2008, Physical and hydrological characterization of Clark's Meadow in the Last Chance Watershed of Plumas County: Report to the Natural Heritage Institute, Mountain Meadows IRWMP, California State University Sacramento, Department of Geology, 38 pp.

http://ceic.resources.ca.gov/catalog/SacramentoRiverWatershedData/PhysicalAndHydrologicalCharacterizationOfClarksMeadow.html

Plug and pond meadow restoration increased groundwater storage. Effects on streamflow were not evaluated.

I.2.2 DeBano, L.F., and Schmidt, L.J., 1989, Improving southwestern riparian areas through watershed management: USDA Forest Service General Technical Report RM-182, 33pp.

http://www.treesearch.fs.fed.us/pubs/37647

A case study in Colorado is described in which ephemeral or intermittent flows were converted to perennial flows by restoration of gullied channels in alluvial headwater valleys in the Alkalai Creek watershed described by Heede (1979; see below). Recovery of streamflow was not observed until after 12 years of project implementation and 7 post-project years. Although perennial flow was restored to the downstream reach of the project, upstream channels remained ephemeral.

I.2.3 Elmore, Wayne, and Beschta, R.L., 1987, Riparian areas: perceptions in management: Rangelands 9(6):260-265.

http://www.rmrs.nau.edu/awa/ripthreatbib/elmore_beschta_riperianareas.pdf

Provides a general discussion of adverse impacts of stream incision on summer baseflows in eastern Oregon rangelands and provides photographic and anecdotal information on improved baseflow volumes and duration for streams restored to aggrading conditions using grazing strategies and vegetative manipulation.

I.2.4 Hammersmark, C., Rains, M., and Mount, J., 2008, Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA: River Research and Applications 24(6): 735-753.

http://onlinelibrary.wiley.com/doi/10.1002/rra.1077/abstract

Plug and pond meadow restoration in Lassen County resulted in higher water table elevations, increased groundwater storage, a non-detectable decrease in total annual streamflow, and a decreased duration of base flow at the midpoint of the restored meadow reach. Baseflow downstream of the restored reach was reported to have increased after restoration, but was not quantified. The decreased mid-meadow baseflow was attributed to increased evapotranspiration and increased downstream groundwater discharge that was not included as streamflow.

I.2.5 Heede, B.H., 1979, Deteriorated watersheds can be restored: a case study: Environmental Management 3(3):271-281

http://www.springerlink.com/content/g4rg7745761vgu56/

Restoration of a watershed in western Colorado using range management and check-dam construction in gullies eroded in alluvial valley floors restored perennial flow to streams within 7 years after restoration.

I.2.6 Klein, L.R., Clayton, S.R., Alldredge, J.R., and Goodwin, Peter, 2007, Long-term monitoring and evaluation of the Lower Red River meadow restoration project, Idaho, USA: Restoration Ecology 15(2):223-239.

http://onlinelibrary.wiley.com/doi/10.1111/j.1526-100X.2007.00206.x/pdf

Evaluation of restoration of a large meadow in Idaho showed that restoration resulted in increased duration, extent, and volume of overbank flooding.

I.2.7 Liang, L., Kavvas, M.L., Chen, Z.Q., Anderson, M., Ohara, N., Wilcox, J., and Mink, L., 2007, Modeling river restoration impact on flow and sediment in a California watershed: Proceedings of ASCE World Environmental and Water Resources Congress, ed. by. Karen C. Kabbes, Conf. in Tampa, Florida, May, 2007.

Not available via internet.

Plug and pond restoration in Last Chance Meadow along a tributary of the Feather River in Plumas County was shown with a modeling approach to increase summer baseflows.

I.2.8 Loheide, S.P. II, and Gorelick, S.M., 2006, Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories: Environmental Science and Technology 40(10):3336-3341.

http://www.clas.ufl.edu/users/jbmartin/website/Classes/Surface_Groundwater/Class%203/Loheide%20and%20Gorelick%20Environ%20Sci%20Tech%202006%20Hypor%20and%20T.pdf

Water temperature data were used to infer increased baseflow in restored meadow reaches relative to unrestored reaches in the upper Feather River watershed (Plumas NF).

I.2.9 Loheide, S.P. II, and Gorelick, S.M., 2007, Riparian hydroecology: a coupled model of the observed interactions between groundwater flow and meadow vegetation patterning: Water Resources Research, vol. 43, W07414

http://www.agu.org/journals/ABS/2007/2006WR005233.shtml

Meadow restoration along tributaries to the Feather River increases groundwater residence time and may contribute to late summer streamflow duration owing to longer groundwater flow paths relative to incised meadows.

I.2.10 Loheide, S.P., and Booth, E.G., 2010, Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater-dependent ecosystems: Geomorphology (article in press).

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V93-50106MJ-2&_user=4250274&_coverDate=05%2F05%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551700173&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=5847b8885034e26e3f9376a1e9293daf&searchtype=a

Effects of channel incision and widening on vegetation and groundwater in alluvial aquifers such as meadows were evaluated. Effects on streamflow were not analyzed.

I.2.11 Ponce, V.M., and Lindquist, D.S., 1990, Management strategies for baseflow augmentation: Proceedings, ASCE Irrigation and Drainage Division, Watershed Management Symposium, Durango, Colorado, July 9-11, 1990.

http://saltonsea.sdsu.edu/watershedplanbaseflowaug313.html

Provides examples of several western mountain meadows where restoration, primarily with check dams, converted ephemeral channels to perennial flow.

I.2.12 Swanson, Sherman, Franzen, Dave, and Manning, Mary, 1987, Rodero Creek: rising water on the high desert: Journal of Soil and Water Conservation 42(6):405-407.

www.jswconline.org/content/42/6/405.extract

Meadow restoration with check dams in northwestern Nevada transformed about a mile of intermittent channel to perennial flow.

I.2.13 Tague, Christina, Valentine, Scott, and Kotchen, Matthew, 2008, Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed: Water Resources Research 44, W10415, 10 pp.

http://environment.yale.edu/kotchen/pubs/stream.pdf

Plug and pond restoration of Trout Creek near Lake Tahoe resulted in higher water-table elevations and increased mid-summer streamflow. Post-restoration streamflow in late summer was about the same as pre-restoration flow.

I.3 Erosion and restoration effects on meadow vegetation in the western United States

This topic is not directly relevant to restoration effects on streamflow, but may be helpful for NEPA analyses of post-restoration vegetation, including no-action alternatives.

I.3.1 Allen-Diaz, B.H., 1991, Water table and plant species relationships in Sierra Nevada meadows: American Midland Naturalist 126:30-43.

http://www.jstor.org/stable/2426147

Plant species composition on meadows at Sagehen Creek (Tahoe NF) were largely controlled by depth to the water table.

I.3.2 Cottam, W.P., 1929, Man as a biotic factor illustrated by recent floristic and physiographic changes at the Mountain Meadows, Washington County, Utah: Ecology 10(4):361-363

http://www.esajournals.org/doi/abs/10.2307/1931143

Historical observations were used to illustrate relations between human land disturbance, meadow erosion, and subsequent shifts to xeric vegetation in a meadow in Utah.

I.3.3 Cottam, W.P., and Stewart, George, 1940, Plant succession as a result of grazing and of meadow desiccation by erosion since settlement in 1862: Journal of Forestry 38:613-626.

http://www.ingentaconnect.com/content/saf/jof/1940/00000038/00000008/art00004

A shift from meadow grasses to junipers was documented and related to gully erosion in a meadow in Utah.

I.3.4 Darroutzet-Nardi, Anthony, D'Antonio, C.M., and Dawson, T.E., 2006, Depth of water acquisition by invading shrubs and resident herbs in a Sierra Nevada meadow: Plant and Soil 285:31-43

http://anthony.darrouzet-nardi.net/works/Darrouzet-Nardi2006b.pdf

Sagebrush in meadows of the Kern Plateau expanded its range owing to gully erosion and lower water-table elevations.

I.3.5 Debinski, D.M., Wickham, Hadley, Kindscher, Kelly, Caruthers, J.C., and Germino, Matthew, 2010, Montane meadow change during drought varies with background hydrologic regime and plant functional group: Ecology 91(6):1672-1681.

http://www.esajournals.org/doi/abs/10.1890/09-0567.1

Vegetation changes during drought in meadows in Yellowstone National Park were documented and related to hydrologic conditions.

I.3.6 Hammersmark, C.T., Rains, M.C., Wickland, A.C., and Mount, J.F., 2009, Vegetation and water-table relationships in a hydrologically restored riparian meadow: Wetlands 29(3):785-797.

http://www.bioone.org/doi/abs/10.1672/08-15.1

Plant communities following plug-and-pond restoration of Bear Meadow in Lassen County followed hydrologic gradients.

I.3.7 Hammersmark, C.T., Dobrowski, S.Z., Rains, M.C., and Mount, J.F., 2010, Simulated effects of stream restoration on the distribution of wet-meadow vegetation: Restoration Ecology 18(6):882-893.

http://onlinelibrary.wiley.com/doi/10.1111/j.1526-100X.2009.00519.x/pdf

A model was used to show an expansion of suitable habitat for mesic vegetation and a decrease in suitable habitat for xeric vegetation following restoration of a wet meadow on Bear Creek in Lassen County.

I.4 Meadow evapotranspiration in the western United States

The publications listed for this topic provide information on rates of meadow evapotranspiration (ET). ET increases after restoration, and may therefore decrease streamflow downstream during summer.

I.4.1 Borrelli, John, and Burman, R.D., 1982, Evapotranspiration from heterogeneous mountain meadows: Water Resources Series No. 86, Wyoming Water Research Center, University of Wyoming, Laramie, WY, 31 pp.

http://library.wrds.uwyo.edu/wrs/wrs-86/abstract.html

Monthly ET rates in wet meadows ranged from 2.8 to 25.0 cm during growing season.

I.4.2 Loheide, S.P. II, and Gorelick, S.M., 2005, A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites: Remote sensing of Environment 98: 182-200.

http://www.feather-river-crm.org/project-files/ETPaper.pdf

ET in eroded meadows in the Feather River watershed ranged from 1.5 to 4 mm/day. ET in restored meadows ranged from 5 to 6.5 mm/day.

I.4.3 Lowry, C.S., and Loheide, S.P. II, 2010, Groundwater-dependent vegetation: quantifying the groundwater subsidy: Water Resources Research 46, W06202, 8 pp.

http://www.agu.org/pubs/crossref/2010/2009WR008874.shtml

ET from groundwater comprised a large proportion of total wet-meadow ET, and reached rates of roughly 3 mm/day.

I.4.4 Sanderson, J.S., and Cooper, D.J., 2008, Ground water discharge by evapotranspiration in wetlands of an arid intermountain basin: Journal of Hydrology 351: 344-359.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4RGM0V9-3&_user=4250274&_coverDate=04%2F15%2F2008&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551778614&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=215d32ef4b2418a74f0259b74b1010a4&searchtype=a

Wet-meadow ET from groundwater was distinguished from total ET, and was found to be related to depth to the water table. Results from a variety of models were compared and assessed. Daily actual ET ranged from roughly 1 to 9 mm/day for wet meadows.

I.4.5 Steinwand, A.L., Harrington, R.F., and Or, D., 2006, Water balance for Great Basin phreatophytes derived from eddy covariance, soil water, and water table measurements: Journal of Hydrology 329(3-4):595-605.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4K0FK06-2&_user=4250274&_coverDate=10%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1551786995&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=241899b90510761cee444c14b943dd7a&searchtype=a

ET of meadows in the Owens Valley near the Inyo NF was evaluated throughout annual cycles. Total growing season ET ranged from 53 to 646 mm. In wet alkali meadows with shallow water tables, groundwater supplied 60 to 81% of total ET. Use of groundwater by plants was correlated with water-table depth and leaf-area index.

I.5 Hydraulics of flow between bedrock and meadow aquifers in the western United States

The articles listed under this topic concern the hydrologic relations between meadow aquifers and their surrounding bedrock aquifers and watersheds. The hydrologic and hydraulic connections between meadows and their watersheds are now widely recognized, and any analysis of restoration effects must consider how water flows from hillslopes through meadows to streams.

I.5.1 Atekwana, E.A., and Richardson, D.S., 2004, Geochemical and isotopic evidence of a groundwater source in the Corral Canyon meadow complex, central Nevada, USA: Hydrological Processes 18:2801-2815.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.1495/abstract

The source of meadow groundwater was found to be groundwater discharged from the surrounding watershed through bedrock.

I.5.2 Hill, B.R., 1990, Groundwater discharge to a headwater valley, northwestern Nevada, USA: Journal of Hydrology 113: 265-283.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4876D4N-4M&_user=4250274&_coverDate=02%2F28%2F1990&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1554647423&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=502b6c0172dbaad5b05795caeee929eb&searchtype=a

An eroded meadow in Nevada allowed direct discharge of groundwater from fractured bedrock to an incised gully. Meadow alluvium had lower permeability than surrounding bedrock, and may have restricted groundwater discharge prior to erosion of the gully.

I.5.3 Hill, B.R., and Mitchell-Bruker, Sherry, 2010, Comment on "A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA": paper published in *Hydrogeology Journal* (2009) 17:229–246, by Steven P. Loheide II, Richard S. Deitchman, David J. Cooper, Evan C. Wolf, Christopher T. Hammersmark, Jessica D. Lundquist: Hydrogeology Journal 18(7):1741-1743.

http://www.springerlink.com/content/5077179318n71301/

This comment and accompanying reply (see Loheide and others, 2009, below) address the issue of the relative permeability of meadow alluvium and surrounding bedrock, and implications for streamflow regimen.

I.5.4 Jewett, D.G., Lord, M.L., Miller, J.R., and Chambers, J.C., 2004, Geomorphic and hydrologic controls on surface and subsurface flow regimes in riparian meadow ecosystems, Chapter 5, p. 124-161, in: Great Basin Riparian Ecosystems, Chambers, J.C., and Miller, J.R. (eds.), Society for Ecological Restoration International, Island Press, Covelo, CA.

http://books.google.com/books?id=irAQvednci4C&pg=PA124&lpg=PA124&dq=jewett+chambers+great+basin+riparian+ecosystems+2004&source=bl&ots=qve4wBC7DK&sig=y8tm15LfWmr9mbewrWyUz5YaTfk&hl=en&ei=0U_tTNKOL4T0swPDzcCqBw&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBkQ6AEwAA#v=onepage&q&f=false

Upward vertical hydraulic gradients of meadows in central Nevada were the result of heterogeneities in meadow alluvium that caused variations in permeability.

I.5.5 Loheide, S.P. II, Deitchman, R.S., Cooper, D.J., Wolf, E.C., Hammersmark, C.T., and Lundquist, J.D., 2009, A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA: Hydrogeology Journal 17:229-246.

http://www.ingentaconnect.com/content/klu/10040/2009/00000017/00000001/00000380

Lower permeability of meadow alluvium, higher rates of groundwater inflow, and a high ratio of lateral to basal groundwater inflow all tend to result in higher meadow water-table elevations.

I.5.6 Lowry, C.S., Deems, J.S., Loheide, S.P. II, and Lundquist, J.D., 2010, Linking snowmelt-derived fluxes and groundwater flow in a high elevation meadow system, Sierra Nevada Mountains, California: Hydrological Processes 24(20):2821-2833.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.7714/abstract

Groundwater levels in Tuolumne Meadows in Yosemite NP were found to be controlled by hillslope sources of snowmelt runoff, snowmelt on the meadow surface, and stream recharge.

I.5.7 Payn, R.A., Gooseff, M.N., McGlynn, B.L., Bencala, K.E., and Wondzell, S.M., 2012, Exploring changes in the spatial distribution of stream baseflow generation during a seasonal recession: Water Resources Research Vol. 48, W04519, 15 pp.

http://watershed.montana.edu/hydrology/Home_files/Payn_etal_baseflow_generation_WRR_2012.pdf

A major increase in summer baseflow was noted within a large meadow in the northern Rocky Mountains despite a lack of any change in bedrock.

I.6 Meadow stratigraphy

The following publications provide information on meadow alluvium, including information useful for inferring hydraulic properties such as specific yield and permeability.

I.6.1 Anderson, R.S., and Smith, S.J., 1994, Paleoclimatic interpretations of meadow sediment and pollen stratigraphies from California: Geology, vol. 22, p. 723-726.

http://geology.geoscienceworld.org/cgi/content/abstract/22/8/723

Nine meadows in the central and southern Sierra Nevada were examined for this study. All had surficial peat deposits of roughly 0.5 to 2 m thickness, and most had subsurface strata composed of fine-grained organic silts with thickness of 1 to 2 m.

I.6.2 Koehler, P.A., and Anderson, R.S., 1994, The paleoecology and stratigraphy of Nichols Meadow, Sierra National Forest, California, USA: Palaeogeography, Palaeoclimatology, Palaeoecology 112: 1-17.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6R-4894VG2-S&_user=4250274&_coverDate=11%2F30%2F1994&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1553447910&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=4a11b509278ecdc4c64d2dfcbf2c2b06&searchtype=a

The stratigraphy of a meadow on the Sierra NF was composed mostly of silty sand, sand, and gravel, with minor amounts of clay and silty clay and no peat or other highly organic strata.

I.6.3 Wood, S.H., 1975, Holocene stratigraphy and chronology of mountain meadows, Sierra Nevada, California: USDA-Forest Service Earth Surface Monograph 4, Pacific Southwest Region.

http://thesis.library.caltech.edu/5570/

This monograph includes a wealth of information on meadow stratigraphy, origins, stability, erosion, groundwater dynamics, evapotranspiration, plant ecology, and chronology.

I.7 Groundwater hydraulics of alluvial aquifers with low-permeability organic strata in other geographic areas

Many meadows in the Sierra Nevada have layers of decomposed peat at their surfaces or buried within alluvial strata. The following articles describe the effects of similar low-permeability organic strata on groundwater-surface water relations in other parts of the world, but have relevance for our understanding of Sierra Nevada meadow hydrology.

I.7.1 Bowden, W.B., Fahey, B.D., Ekanayake, J., and Murray, D.L., 2001, Hillslope and wetland hydrodynamics in a tussock grassland, South Island, New Zealand: Hydrological Processes 15: 1707-1730.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.235/abstract

Water storage in bog peats was insufficient to support baseflows for longer than a few days in a New Zealand watershed.

I.7.2 Branfireun, B.A., and Roulet, N.T., 1998, The baseflow and storm flow hydrology of a Precambrian shield headwater peatland: Hydrological Processes 12: 57-72.

http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-1085(199801)12:1%3C57::AID-HYP560%3E3.0.CO;2-U/abstract

Groundwater emerging below a peat layer maintained baseflow in a stream in a small headwater wetland in Ontario.

I.7.3 Langhoff, J.H., Rasmussen, K.R., and Christensen, Steen, 2005, Quantification and regionalization of groundwater-surface water interaction along an alluvial stream: Journal of Hydrology 320:342-358.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4H6GPWC-1&_user=4250274&_coverDate=04%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_u

rlVersion=0&_userid=4250274&md5=fc5b890f8784d251605da642039c1047&searchtype=a

A peat layer below an alluvial streambed was found to limit groundwater discharge to the stream despite a large hydraulic gradient.

I.7.4 McGlynn, B.L., McDonnell, J.J., Shanley, J.B., and Kendall, C., 1999, Riparian zone flowpath dynamics during snowmelt in a small headwater catchment: Journal of Hydrology 222:75-92.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-3XBTSHK-6&_user=4250274&_coverDate=09%2F13%2F1999&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1552938308&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=29c4c2acd4605cc06478a68b04eef6b9&searchtype=a

Saturated hydraulic conductivity of peat ranged from 141 to 267 mm/hr (4 x 10^{-3} to 7 x 10^{-3} cm/s) in the riparian zone, and peat was underlain by a much lower conductivity till layer. Steep upward hydraulic gradients were observed in the riparian zone, and were related to streamflow. Low permeability layers caused a "backup" of flow in the riparian zone with increased hydraulic gradients.

I.7.5 O'Brien, A.L., 1988, Evaluating the cumulative effects of alteration on New England wetlands: Environmental Management 12(5):627-636.

http://www.springerlink.com/content/rtp5139133t80260/

Low-permeability organic wetland sediments can significantly influence groundwater flow patterns and discharge. Destruction of wetlands may result in decreased hydraulic heads, water table declines, and altered streamflow regimen.

I.7.6 Reeve, A.S., Siegel, D.I., and Glaser, P.H., 2000, Simulating vertical flow in large peatlands: Journal of Hydrology 227: 207-217.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-3YRVDK7-G&_user=4250274&_coverDate=01%2F31%2F2000&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1553409453&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=72bf0bffc9e96a807306afc2278d3a99&searchtype=a

The extent of upwardly vertical flow and vertical hydraulic gradients in peatlands was controlled by permeability contrasts between peat and underlying mineral soil.

I.7.7 Vidon, P.G.F., and Hill, A.R., 2004, Landscape controls on the hydrology of stream riparian zones: Journal of Hydrology 292:210-228.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4BYNR6V-B&_user=4250274&_coverDate=06%2F15%2F2004&_rdoc=1&_fmt=high&_orig=searc

h&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=111728ffa3e387a8125dac8075830be5&searchtype=a

Saturated permeability of peat was determined to be 10^{-5} cm/s. Horizontal/vertical permeability anisotropy in peats can range from 0 to 1,000. Low-permeability peats caused groundwater flow to be refracted upward toward stream channels and flood plains, resulting in year-long surface saturation at groundwater discharge zones.

I.7.8 Wong, L.S., Hashim, R., and Ali, F.H., 2009, A review on hydraulic conductivity and compressibility of peat: Journal of Applied Sciences 9(18):3207-3218.

http://www.scialert.net/pdfs/jas/2009/3207-3218.pdf

Vertical hydraulic conductivity of peat ranged from 10^{-3} to 10^{-6} cm/s, and was lower for amorphous than fibrous peat.

I.8 Groundwater hydraulics of alluvial aquifers with low-permeability non-organic confining strata in other geographic areas

The publications listed below describe groundwater-surface water interactions affected by nonorganic low-permeability strata in other areas. These studies have relevance for some Sierran meadows owing to their descriptions of interactions between confined riparian aquifers and streams.

I.8.1 Andersen, M.S., and Acworth, R.I., 2009, Stream-aquifer interactions in the Maules Creek catchment, Namoi Valley, New South Wales, Australia: Hydrogeology Journal 17: 2005-2021.

http://www.springerlink.com/content/rtp5139133t80260/

Lithologic heterogeneities that determine permeability were major determinants of patterns of groundwater discharge to a stream.

I.8.2 Banks, E.W., Simmons, C.T., Love, A.J., Cranswick, R., Werner, A.D., Bestland, E.A., Wood, M., and Wilson, T., 2009, Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface water interaction: a conceptual model (Australia): Hydrogeology Journal 17:1969-1989.

http://www.springerlink.com/content/rtp5139133t80260/

Deep groundwater flow through fractured metamorphic bedrock was a major source of streamflow.

I.8.3 D'Amore, D.V., Stewart, S.R., Huddleston, J.H., and Glasmann, J.R., 2000, Stratigraphy and hydrology of the Jackson-Frazier wetland, Oregon: Soil Science Society of America Journal 64:1535-1543.

https://www.soils.org/publications/sssaj/articles/64/4/1535

A confining layer composed of smectite clays resulted in artesian conditions in a wetland near Corvallis.

I.8.4 Katsuyama, Masanori, and Ohte, Nobuhito, 2005, Effects of bedrock permeability on hillslope and riparian groundwater dynamics in a weathered granite catchment: Water Resources Research vol. 41, W01010, 11 pp.

http://www.agu.org/journals/ABS/2005/2004WR003275.shtml

Groundwater flow through weathered granite was an important source for a headwater riparian zone and for streamflow in a small mountainous watershed in Japan. Saturated hydraulic conductivity of unweathered granitic bedrock was roughly 6 x 10^{-4} cm/s, while weathered bedrock had a permeability 2 orders of magnitude higher.

I.8.5 Konrad, C.P., 2006, Location and timing of river-aquifer exchanges in six tributaries to the Columbia River in the Pacific Northwest of the United States: Journal of Hydrology 329: 444-470.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4JRM0NR-3&_user=4250274&_coverDate=10%2F15%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1627378435&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=6574304fe165ab648d0762222cf5acd7&searchtype=a

Permeability contrasts in alluvial aquifers were found to be one of 3 major factors affecting the magnitudes of flows between rivers and aquifers in the Columbia River basin.

I.8.6 Morrice, J.A., Valett, H.M., Dahm, C.N., and Campana, M.E., 1997, Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams: Hydrological Processes 11:253-267.

http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-1085(19970315)11:3%3C253::AID-HYP439%3E3.0.CO;2-J/abstract

The flow direction of groundwater discharging to an alluvial stream was related to local variation in hydraulic gradients.

I.8.7 Salve, Rohit, and Tokunaga, T.T., 2002, Seepage response along an alluvial valley in a semi-arid catchment in north-central California: Hydrological Processes 16: 65-86.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.285/abstract

Stratigraphic heterogeneities and varying permeabilities within valley alluvium in the central Coast Ranges resulted in temporary confining conditions that produced vertically-upward flow and exfiltration of groundwater.

I.8.8 Urbano, Lensyl, Waldron, Brian, Larsen, Dan, and Shook, Heather, 2006, Groundwater-surface water interactions at the transition of an aquifer from unconfined to confined: Journal of Hydrology 321:200-212.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-4H4T3CN-6&_user=4250274&_coverDate=04%2F30%2F2006&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1552907627&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=b1262a0da7f78b5aaface042a3c99d0c&searchtype=a

A 3-dimensional steady-state groundwater model was used to evaluate the effects of an upper confining clay stratum on groundwater discharge to a stream. The results showed that groundwater discharge to the stream increased sharply at the upstream boundary of the confining unit. The model was also used to evaluate the effects of river entrenchment that breached the confining layer. Entrenchment resulted in sharp increases in groundwater discharge to the stream.

I.9 Alluvial channel incision (gully erosion) effects on streamflow in other geographic areas

These studies are summarized owing to expected similarities between the effects of channel incision of alluvial aquifers in various areas worldwide with meadow erosion in the western U.S.

I.9.1 Costa, F.M., and de Almeida Prado Bacellar, Luis, 2007, Analysis of the influence of gully erosion in the flow pattern of catchment streams, Southeastern Brazil: Catena 69: 230-238.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VCG-4KDBM9F-1&_user=4250274&_coverDate=04%2F15%2F2007&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=ed821e963953200e805e3ad171db9be0&searchtype=a

Gully erosion of alluvial and colluvial valleys resulted in higher peak flows and lower base flows. See reference number 4. below for additional analyses of the effects of gully erosion on confined groundwater flows.

I.9.2 De A.P. Bacellar, Coehlo Netto, A.L., and Lacerda, W.A., 2005, Controlling factors of gullying in the Maracuja Catchment, Southeastern Brazil: Earth Surface Processes and Landforms 30:1369-1385.

http://onlinelibrary.wiley.com/doi/10.1002/esp.1193/pdf

Gully erosion was related to breaching of a confining clay layer overlying a more permeable saprolite aquifer by roads and ditches.

I.9.3 Larkin, R.G., and Sharp, J.M., Jr., 1992, On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers: Geological Society of America Bulletin 104(12): 1608-1620.

http://bulletin.geoscienceworld.org/cgi/content/abstract/104/12/1608

Alluvial aquifers in various locations throughout the United States were classified either as baseflow (groundwater flow perpendicular to the stream channel) or underflow (groundwater flow parallel to the stream). Factors important in determining the relative proportions of groundwater flowing toward the channel or down the axis of the valley included channel gradient, channel depth, and sinuosity.

I.9.4 Nogueras, Pascual, Burjachs, Francesc, Gallart, Francesc, and Puigdefabregas, Joan, 2000, Recent gully erosion in the El Cautivo badlands (Tabernas, SE Spain): Catena 40:203-215.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VCG-40GJDN8-6&_user=4250274&_coverDate=06%2F15%2F2000&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1606478070&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=9d689683506fd8a80fc5a68242a7b4d2&searchtype=a

This study infers a natural groundwater storage function for valley fills that remain uneroded by gullies. However, no data on this topic are presented.

I.9.5 Rutherfurd, Ian, Hoang, Tam, Prosser, Ian, Abernethy, Bruce, and Jayasuriya, Nira, 1996, The impacts of gully networks on the time-to-peak and size of flood hydrographs, in: Hydrology and Water Resources Symposium 1996: Water and the Environment, Preprints of papers, p. 397-402.

http://search.informit.com.au/documentSummary;dn=364553489879848;res=IELENG>ISBN:0858256495

Gully erosion of alluvial headwater valleys in Australia increased flood peaks by 12 to 20% and decreased time to peak by 20 to 24% for the 100-year and 1-year floods, respectively.

I.9.6 Schilling, K.E., Zhang, Y.K., and Drobney, P., 2004, Water table fluctuations near an incised stream, Walnut Creek, Iowa: Journal of Hydrology 286(1-4), p. 236-248.

http://www.sciencedirect.com

Stream incision of 3 m into an alluvial valley floor increased flood peaks and reduced the time between peak rainfall and streamflow. Groundwater storage was reduced. Hydraulic gradients toward the stream were increased.

I.9.7 Shields, R.D., Jr., Knight, S.S., and Cooper, C.M., 1994, Effects of channel incision on baseflow stream habitats and fishes: Environmental Management 18(1):43-57.

http://www.springerlink.com/content/l8ph1q731j370186/fulltext.pdf

An unincised reference stream had higher autumn baseflow than 3 incised streams in Mississippi.

I.10 Hydrologic functions of headwater wetlands in other geographic areas

Although many more publications are available, these selected articles are summarized here to show that the hydrologic functions of small alluvial headwater wetlands are not well understood in many areas worldwide. These articles illustrate approaches that have been used to evaluate streamflow regulation in headwater wetlands and demonstrate that wetlands that appear to be generally similar may have significantly different hydrologic behaviors.

I.10.1 Bullock, Andrew, 1992, Dambo hydrology in southern Africa—review and assessment: Journal of Hydrology 134(1-4):373-396.

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V6C-48C7D50-5X&_user=4250274&_coverDate=06%2F30%2F1992&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1554706096&_rerunOrigin=google&_acct=C000052423&_version=1&_urlVersion=0&_userid=4250274&md5=dcf5d0f9a6c5ef3c757a37140c0055c9&searchtype=a

This article reviews published research on the hydrologic functions of dambos (small alluvial headwater wetlands in Africa), notes a lack of consensus of the effects of dambos on low flows, and proposes that dambos may reduce baseflows.

I.10.2 Bullock, Andy, and Acreman, Mike, 2003, The role of wetlands in the hydrological cycle: Hydrology and Earth Systems Sciences 7(3):358-389.

http://www.hydrol-earth-syst-sci.net/7/358/2003/hess-7-358-2003.html

This article reviews published information on the subject and classifies results based on types of wetlands worldwide. Most studies of wetland effects on baseflows showed decreases.

I.10.3 Jencso, K.G., McGlynn, B.L., Gooseff, M.N., Bencala, K.E., and Wondzell, S.M., 2010, Hillslope hydrologic connectivity controls riparian groundwater turnover: Implications of catchment structure for riparian buffering and stream water sources: Water Resources Research, vol. 46, W10524, 18 pp.

http://watershed.montana.edu/hydrology/Home_files/Jencso%20McGlynn%20et%20al%20%202009WR008818%20(1).pdf

The size of riparian zones was found to significantly affect their role in affecting the magnitude and timing of streamflow.

I.10.4 Montreuil, Olivier, Cudennec, Christophe, and Merot, Philippe, 2011, Contrasting behavior of two riparian wetlands in relation to their location in the hydrographic network: Journal of Hydrology 406: 39-53.

http://www.sciencedirect.com/science/article/pii/S0022169411003775

An upstream riparian wetland had lower hydraulic conductivity, higher and more vertical (upward) groundwater flow gradients, longer and higher periods of saturation, and greater groundwater discharge to the stream channel in comparison to a downstream wetland in Brittany (France). The downstream wetland had a more deeply incised channel.

I.10.5 Morley, T.R., Reeve, A.S., and Calhoun, A.J.K., 2011, The role of headwater wetlands in altering streamflow and chemistry in a Maine, USA catchment: Journal of the Water Resources Association 47(2): 337-349.

http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2010.00519.x/abstract

Small headwater wetlands were found to regulate the discharge of shallow groundwater from hillslopes to streams and thereby increase the volume and duration of baseflows in a central Maine watershed.

I.10.6 Prosser, I.P., Chappell, John, and Gillespie, Richard, 1994, Holocene valley aggradation and gully erosion in headwater catchments, South-Eastern highlands of Australia: Earth Surface Processes and Landforms 19: 465-480.

http://onlinelibrary.wiley.com/doi/10.1002/esp.3290190507/pdf

Swampy meadows were inferred to increase peak flows owing to greater proportions of saturated overland flow relative to valleys eroded by gullies. Effects of meadows or erosion on baseflows were not assessed.

I.10.7 Riddell, E.S., Lorentz, S.A., and Kotze, D.C., 2010, A geophysical analysis of hydro-geomorphic controls within a headwater wetland in a granitic landscape, through ERI and IP: Hydrology and Earth System Sciences 14: 1697-1713.

http://www.hydrol-earth-syst-sci-discuss.net/7/1973/2010/hessd-7-1973-2010-print.pdf

Illuvial low-permeability "clay plugs" were found to be important features controlling groundwater flow in an eroding headwater wetland in South Africa.

I.10.8 Smakhtin, V.U., and Batchelor, A.L., 2005, Evaluating wetland flow regulating functions using discharge time-series: Hydrological Processes 19:1293-1305.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.5555/pdf

Regional flow-duration curves and paired (upstream/downstream) streamgages were used to evaluate streamflow regulation in a large flood-plain wetland similar in South Africa. The wetland had many similarities to alluvial meadows in the western U.S. The wetland was found to attenuate flood peaks and increase baseflows.

I.10.9 Von der Heyden, C.J., 2004, The hydrology and hydrogeology of dambos: a review: Progress in Physical Geography 28(4):544-564.

http://ppg.sagepub.com/content/28/4/544.abstract

This paper reviews available information on hydrology of dambos (small alluvial headwater wetlands in Africa) and describes the current lack of consensus on their hydrological functions, including maintenance of low flows.

Appendix J: Preliminary Assumptions

J.1 Overview

This section provides a preliminary outline of a biophysical pathway and the economic costs associated with the Mokelumne Avoided Cost Study. Steps in the biophysical pathway, as analyzed in the study, are listed numerically and seek to encompass forest stand conditions, fuel and vegetation management treatments, wildfire severity, erosion of sediment into water storage and conveyance facilities, bark beetle-caused tree mortality, and economic costs. There are numerous assumptions and hypotheses that fall under each step of the biophysical pathway, which we attempt to capture here.

This analysis does not cover some related biophysical processes and economic activities, such as:

- Impacts upon bird, fish and wildlife habitat.
- Impacts upon forest cover, snowpack accumulation and duration, and the timing of water delivery.
- Public recreation activity and impact upon campgrounds, signage, trails, patterns of use, and associated local economic activity.
- Smoke, air pollution, air quality, and impact upon people's respiratory health.
- Impacts upon cultural resources.

J.2 Assumptions

1. Mid-to-low elevation forests in the Mokelumne drainage evolved with fire as a key process, but are now at risk of uncharacteristically high severity and stand-replacing wildfire due largely to the following factors:
    - Wildfire is a natural phenomenon in the Sierra Nevada but has been unnaturally suppressed.
    - Lightning strikes are a frequent and a natural source of ignition that will continue into the future.
    - Anthropogenic sources of ignition will likely continue and perhaps increase as the human population grows and recreation and economic activity increases.
    - Some timber management practices over the past 100+ years have inadvertently promoted fire-prone stand conditions.
    - Fire suppression practices over the past 100+ years that have inadvertently promoted fire-prone stand conditions.
    - Climate change is expected to influence future wildfire behavior, although the exact direction of climate change in the Mokelumne River drainage is uncertain. Forecasting models generally agree on future conditions being warmer, but there is uncertainty over whether it will be drier or wetter in the Mokelumne.

2. The probability of ignition for future wildfire is largely determined by:
    - Human sources of ignition are related to road density, campgrounds, and proximity to homes and developed areas.

- Natural ignitions are related to weather and topography.
- The spatial pattern and frequency of historic fire events.
- Fuel moisture levels.
- Fuel types.
- Surface fuel distribution, volume, and structure (e.g. light and airy vs. dense and compacted).
- Forest stand conditions.
- Weather conditions; wind in particular.
- The spatial pattern and frequency of bark beetle/tree mortality events.

3. The spatial area, the spatial pattern, and the severity of future wildfire events is largely determined by:
    - Weather conditions; particularly wind speed and direction, as well as air temperature.
    - Fuel moisture levels.
    - Fuel types.
    - Relative humidity.
    - Eastern wind events.
    - Surface fuel volume and structure (e.g. light and airy vs. dense and compacted).
        - Including fuels associated with bark beetle/tree mortality events.
    - Forest stand conditions.
    - Topography and aspect.
    - Fire suppression feasibility and effectiveness.
    - Spatial distribution of recently burned areas, fuel reduction treatments, fuel breaks, and roads.
    - Fire spotting from lofting burning embers ahead of the fire.

4. Forests in the Mokelumne drainage are highly susceptible to bark beetles and subsequent high levels of tree mortality due largely to the following factors:
    - Management practices over the past 100 years have inadvertently promoted bark beetle-prone stand conditions.
        i. High tree density.
        ii. Age class and species composition differ from historical conditions.
    - High density stands may be more water-stressed.
    - Protracted dry periods are common in the Sierra Nevada.

5. The probability of bark beetle infestations and its corresponding severity and spatial pattern is largely determined by:
    - Stand elevation.
    - Drought conditions (severity and time period).
    - Forest stand conditions.
        i. Species composition.
        ii. Tree size.

iii. Density.

- Spatial distribution of fuel and vegetation management treatments.
- Distance to burned sites.

6. Fuel and vegetation management treatments that change forest stand conditions can change future wildfire behavior and bark beetle infestation levels in terms of spatial area, spatial pattern, and severity. The primary stand level attributes that contribute to fire behavior and susceptibility to bark beetles are:
   - Percent canopy cover affecting surface winds.
   - Height to live crown (or crown base height).
   - Tree species distribution per unit area.
   - Stand density and diversity.
   - Canopy bulk density affecting continuing spread of a crown fire.
   - Vegetation height affecting flame length.
   - The amount of duff, ladder, and surface fuels.

7. The economic cost of fuel and vegetation management treatments on a specific stand can be estimated based on the following attributes:
   - Stem density per unit area.
   - Basal area per unit area.
   - Percent tree canopy cover.
   - Tree species.
   - Tree size class distribution.
   - Type of treatment (e.g. thin from below; thin and masticate; prescribed fire; etc.).
   - Topography, slope, and rockiness.
   - Accessibility in terms of road access.
   - Distance of transport (e.g. to mills, co-generation facilities, sort yards).
   - Prevailing prices for logs and wood chips.
   - Price of diesel fuel.
   - Crew availability and associated costs.
   - Administrative restrictions on operations such as limited operating periods and complexity of treatment prescriptions.

8. Erosion of sediment after wildfire can be much higher than pre-wildfire conditions in forested landscapes. The timing and volume of sediment erosion after wildfire is largely determined by:
   - Wildfire severity, spatial area, and spatial pattern.
   - Soil characteristics.
   - Amount of bare soil after wildfire.
   - Snow and rainfall weather patterns up to 10 years after the wildfire event.
   - Topography.
   - Condition of roads.
   - Probability of landslide and debris flows.

- Condition of meadows and riparian corridors after fire, as a filter to sediment movement.
- Condition of the watershed before fire in relation to recent or historic human impacts from trails, roads, mining, livestock grazing, and timber harvest practices.

9. A net increase in the rate of sediment erosion after wildfire can affect water and electric utilities from the following processes:
    - Sediment may enter water storage facilities such as reservoirs.
    - Sediment may enter or damage water conveyance facilities such as flumes and canals.
    - Sediment may cover/damage out roads and other infrastructure.
    - Sediment may damage hydroelectric turbines and machinery.
    - Sediment may damage water filtration systems.
    - Sediment may cause a decline in water quality for municipal use.
    - Sediment entering the water supply may transport or facilitate mobilization of nitrogen, phosphorous, heavy metals, and other contaminants.

10. The economic costs of sediment erosion can be forecast based upon:
    - Spatial connectivity between wildfire probability, wildfire severity, soil erosion severity, and water storage & conveyance facilities.
    - Forecasts of sediment mobilization and transport from terrestrial sources into stream and river channels.
    - Forecasts of sediment transport through stream and river channels and into water storage and conveyance facilities. Forecasts of costs to dredge reservoirs and clean conveyance facilities.
    - Forecasts of sediment transport from water storage and conveyance facilities and into hydroelectric facilities. Forecasts of costs to change hydroelectric operations or repair/replace machinery and parts.
    - Forecasts of costs associated with facility downtime until a sediment event subsides.
    - Forecasts of sediment transport into water treatment facilities. Increased water treatment costs or costs associated with alternative sources of water or power.

11. Future tree mortality caused by wildfire or bark beetles will result in damage and loss to public and private landowners, in addition to costs associated with erosion of sediment. The economic costs of damage and loss can be forecast based upon spatial overlap between wildfire probability and severity, bark beetle infestation probability and severity, and improvements. Owners and insurers have an important role to play in forecasting the economic costs of damages and losses from wildfire and bark beetles. Categories of ownership include:
    - Government agencies (US Forest Service, Bureau of Land Management, State of California, County): buildings, facilities, campgrounds, signage, equipment, fences, bridges, habitat, and merchantable timber.

- Private small-scale landowners (0-50 acres): homes, barns, buildings, possessions, equipment, livestock, and fences.
- Private medium-scale land owners (51-1,000 acres): homes, barns, buildings, possessions, equipment, livestock, fences, and merchantable timber.
- Private large-scale landowners (>1,000 acres): buildings, facilities, lumber mills, equipment, livestock, fences, bridges, and merchantable timber.
- Water and electric utilities: buildings, facilities, fences, signs, campgrounds, equipment, roads, bridges, electric transmission lines, water conveyance facilities, hydroelectric power facilities, and merchantable timber.

12. Ecosystem services that currently have limited or no defined economic value can be impaired or destroyed by bark beetle infestations and wildfires. These include:
    - Habitat.
    - Air Quality.
    - Water.
    - Meadow function.
    - Aesthetics (e.g. the value people place on living in a beautiful area).
    - Carbon sequestration.

13. Future wildfire and bark beetle outbreaks will have other direct and indirect costs that vary in relation to spatial area, spatial pattern, and severity. Other direct costs include:
    - Fire suppression costs.
    - Bark beetle prevention costs.
    - Hazard tree mitigation costs.
    - Restoration and erosion control costs.
    - Litigation costs.
    - Loss of property value.
    - Replacement of damaged power lines.

14. Salvage logging may be a source of revenue after tree mortality events, based upon:
    - Condition of standing dead timber.
    - Ecological impact of salvage logging.
    - Accessibility of site.

15. The upper Mokelumne drainage covers over 350,000 acres and fuel and vegetation management treatments across the entirety of its forested lands is not possible due to a number of factors, including:
    - Slope.
    - Access.
    - Cost.
    - Endangered species.
    - Wilderness designation.

16. Decisions on where to implement fuel and vegetation management treatments (high-priority areas) will be made based upon an analysis of a number of factors, including:
    - Access.
    - Slope.
    - Vegetation type.
    - Stand health.
    - Erosion potential.
    - Infrastructure and community proximity.
    - Fire probability.
    - Probability of high-intensity fire.
    - Greatest reduction of threat per unit investment.
    - Overlap with goals for later phases of the project.
    - Overlap with other projects.
    - Proximity to cultural resources.
    - Habitat.
    - Matrix of ownership and owners' management goals.

17. Landslides in the Mokelumne watershed may occur due to the following factors:
    - Bare soils.
    - Insufficient root structure.
    - Soil type.
    - Slope.
    - Precipitation type, frequency, and magnitude.
    - Disturbance.
    - Roads.