


MOKELUMNE WATERSHED AVOIDED COST ANALYSIS:

Why Sierra Fuel Treatments Make Economic Sense

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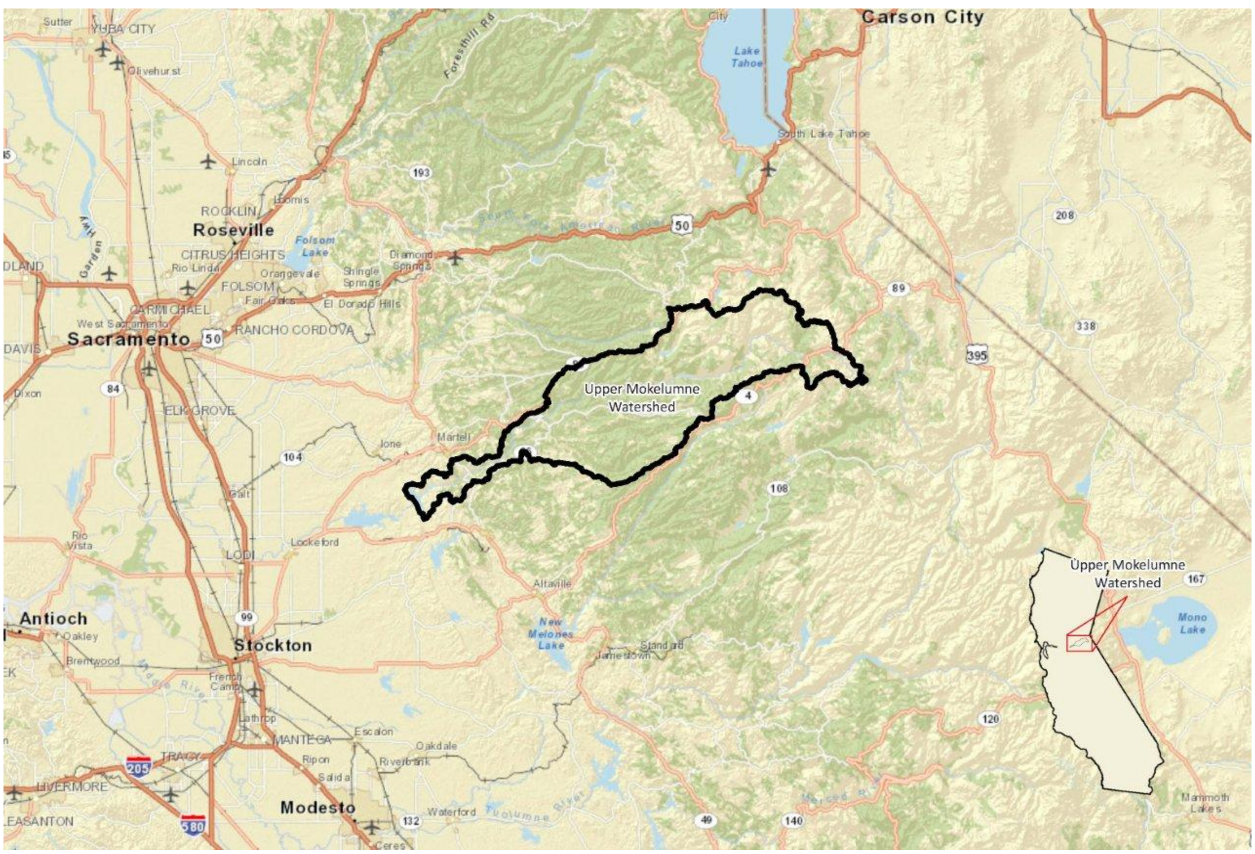
Chapter 3: Model Results—Fuel treatments effects on fire behavior, erosion, and debris flows

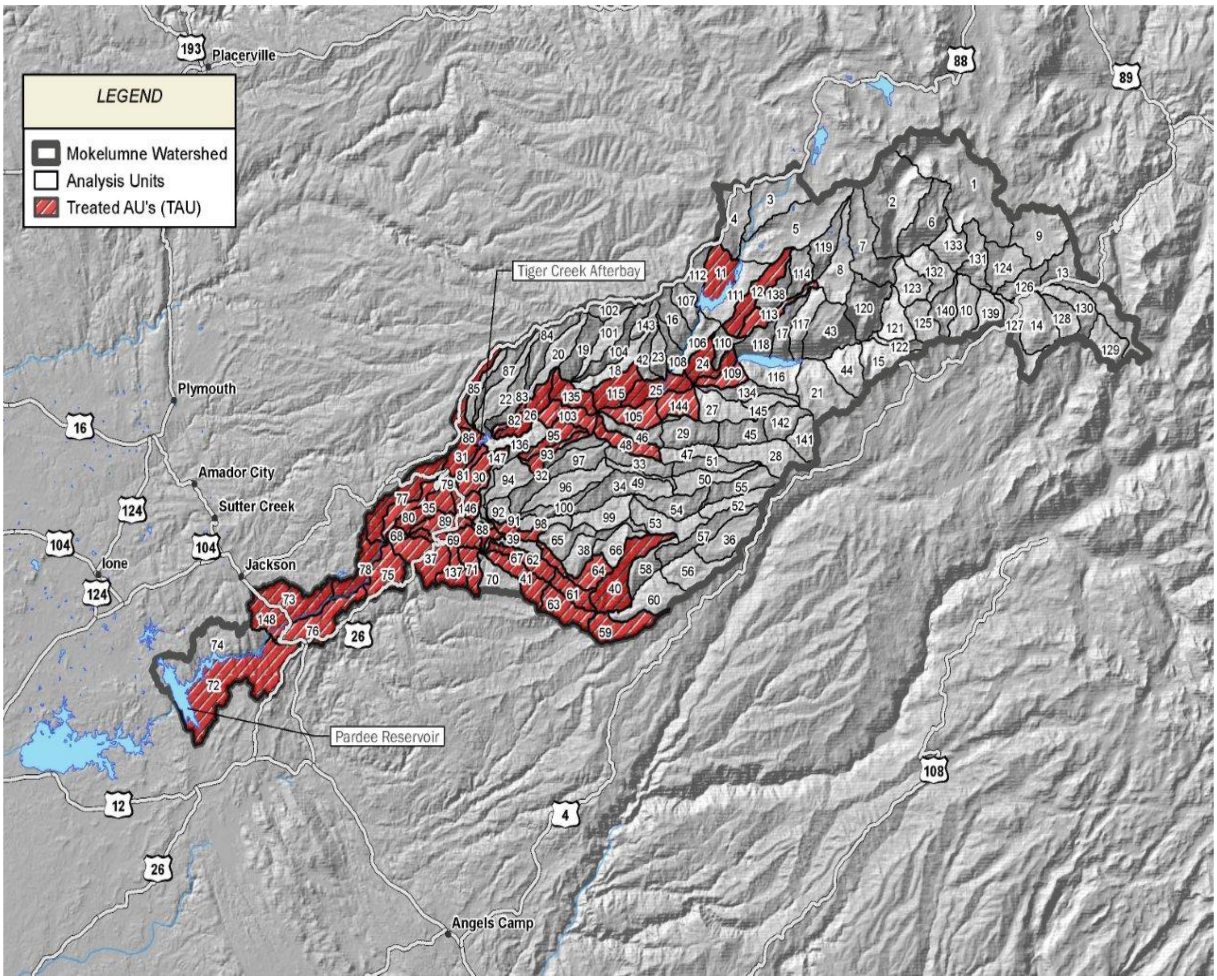
For this analysis we used a series of process-based models to represent existing wildfire and sedimentation conditions of the upper Mokelumne watershed, and then to estimate the effects of fuel treatments on fire behavior and erosion (Figure 3.1; see Appendices A-E for detailed information about the 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.

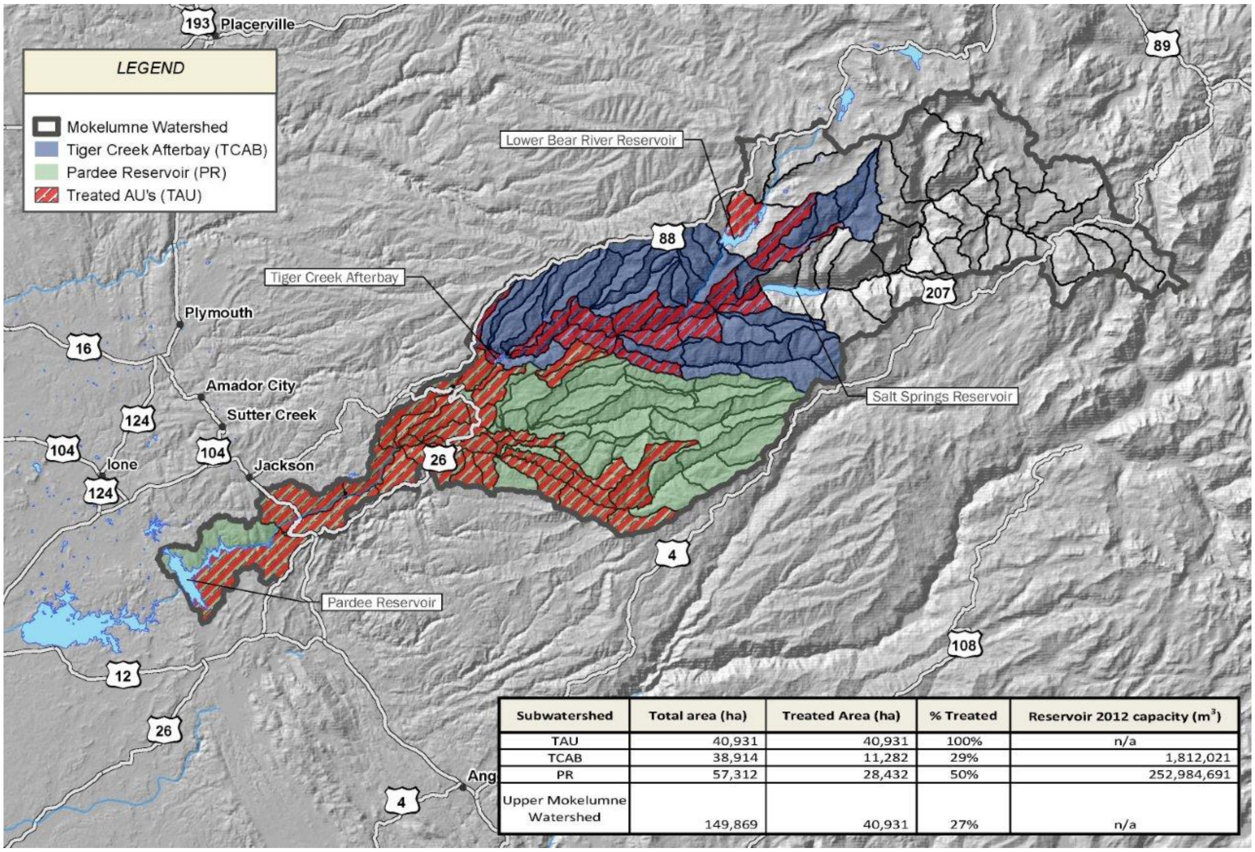
- *Pardee Reservoir Watershed (PR)*: The undammed 57,000 ha catchment draining to the East Bay Municipal Utility District water supply reservoir (Figure 3.3). This catchment includes all lands downstream of the TCAB, and while some fraction of sediment delivered to TCAB does make it downstream of the 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

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[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		

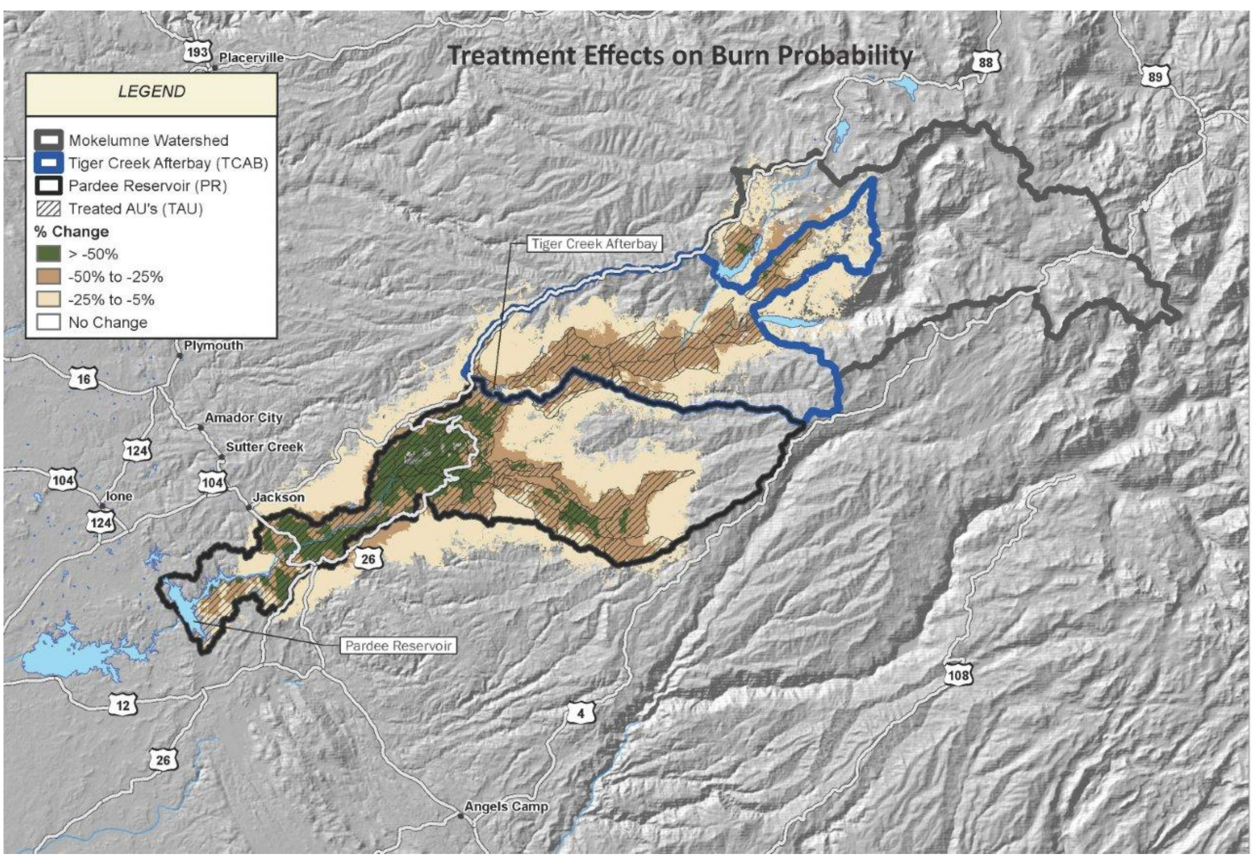
3.4 Landscape Analysis

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.

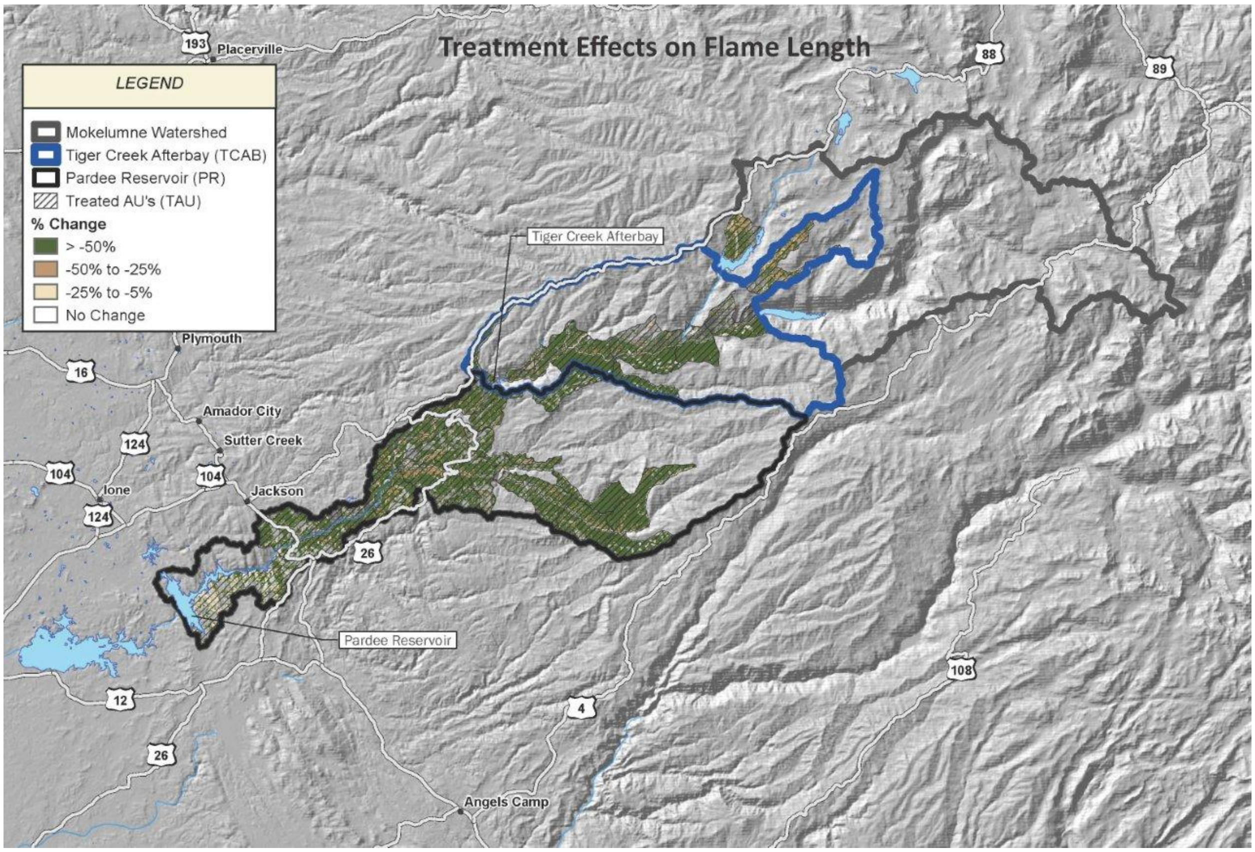
The comparisons of PreT and PostT fire behavior illustrate the significant effect fuel treatments can have on the likelihood and intensity of fire, as well as on the resulting erosion rates (Table 3.5). The 90th percentile burn probability, from the existing conditions (PreT) model, is 0.79%, which means 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

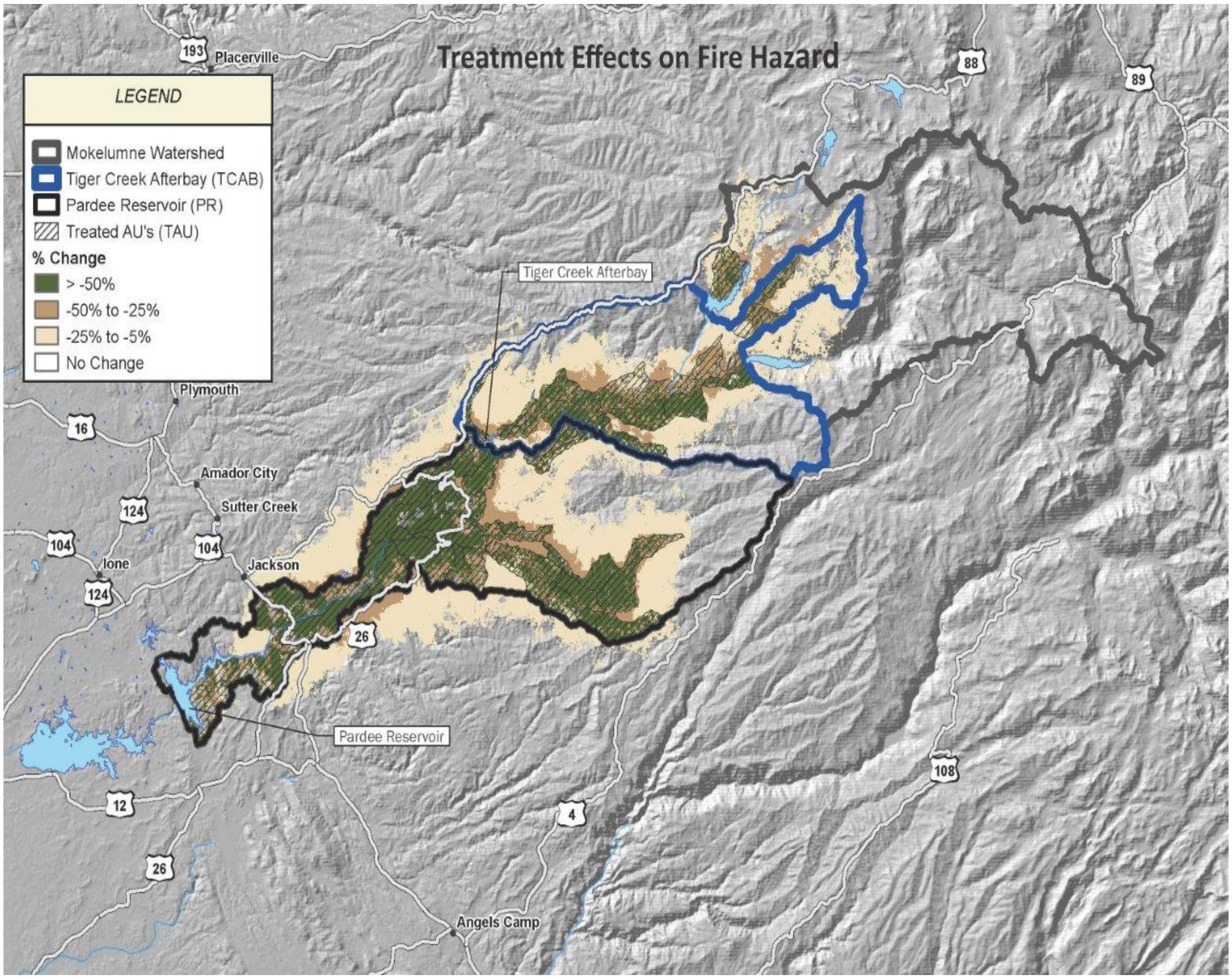
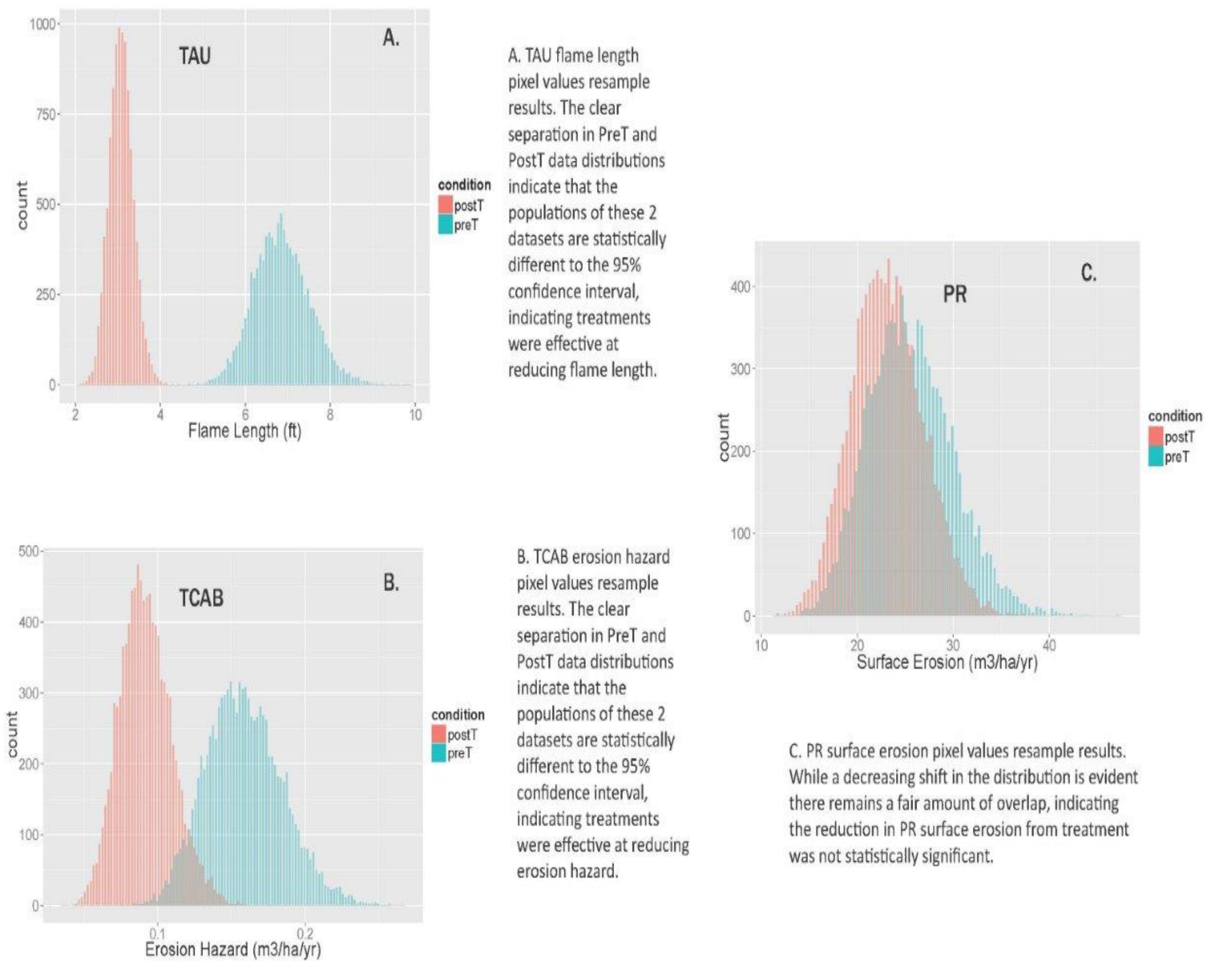


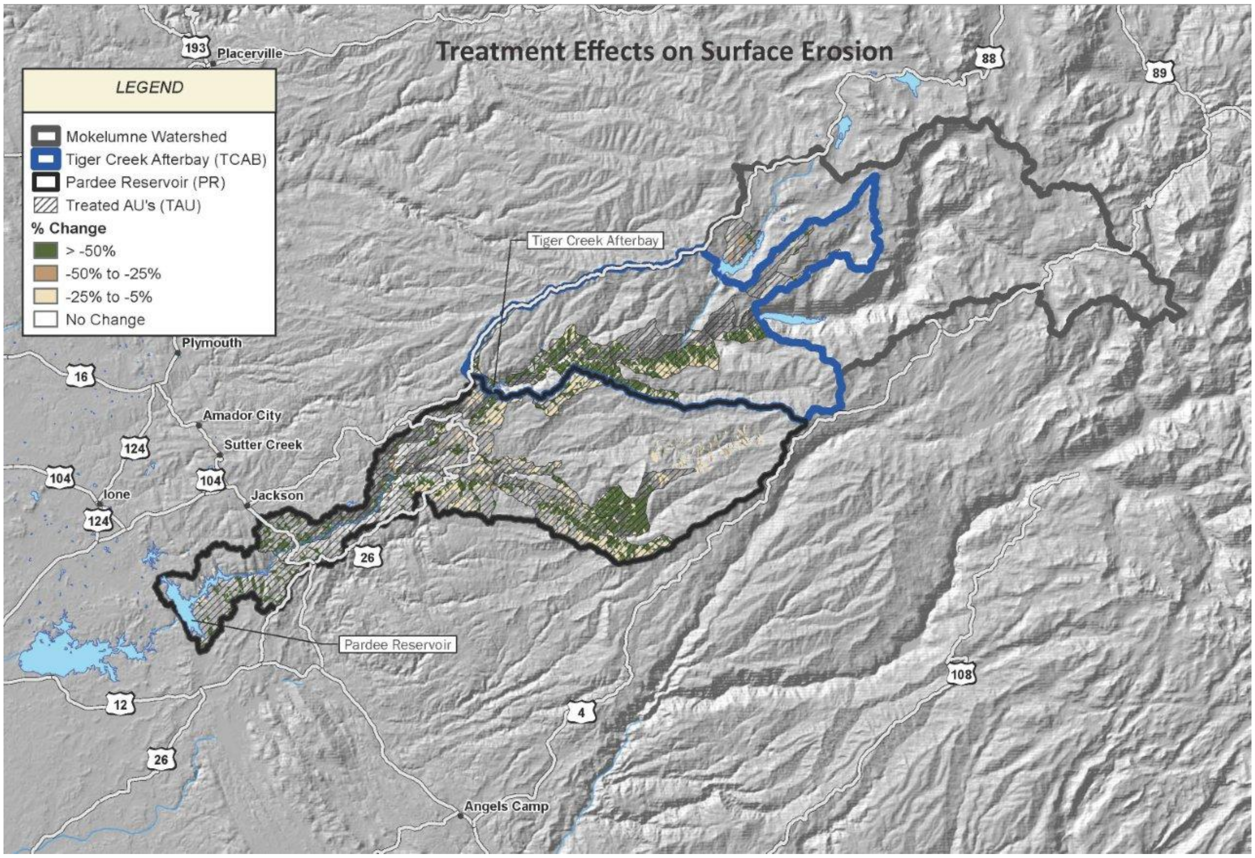
Figure 3.7, Graph A presents the results of the relative change in flame length from the TAU following statistical analysis. The data distribution of the flame length of both datasets and the clear separation of the distributions indicate that these datasets are statistically different at the 95% confidence 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

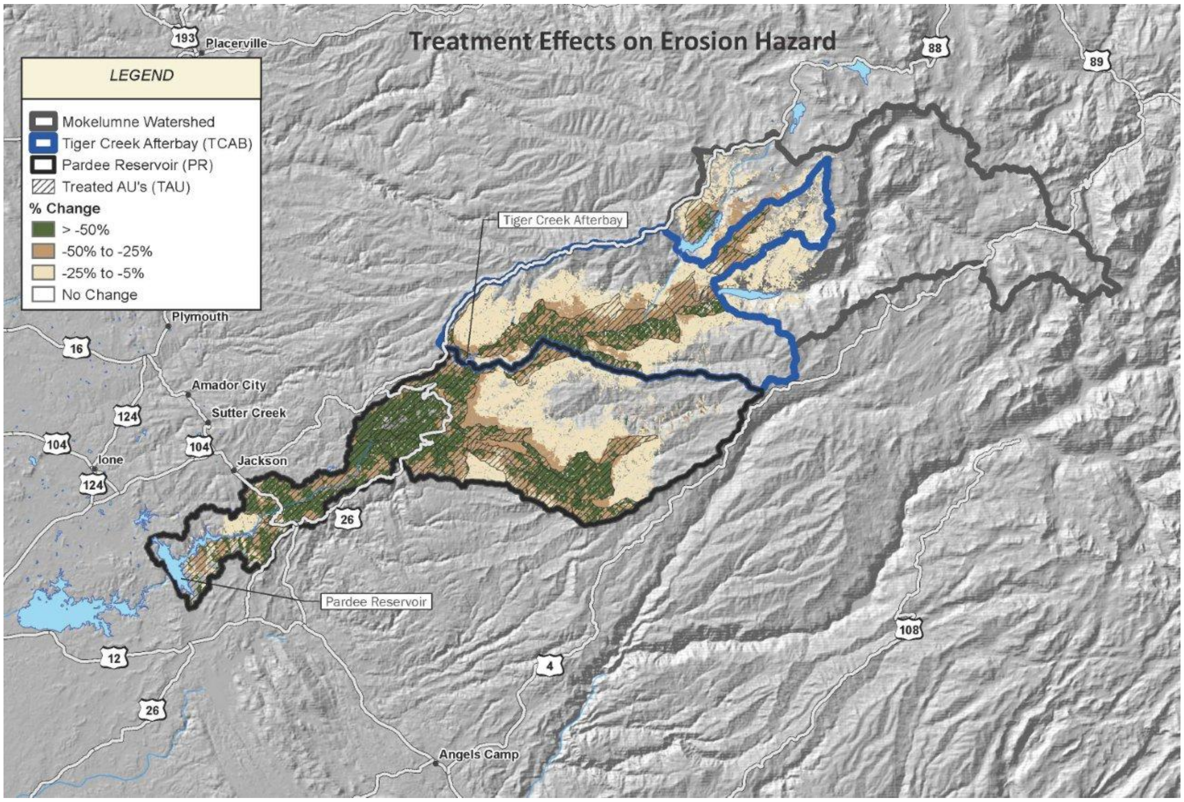


Figure 3.10: Relative change in debris flow volumes as a result of treatment (m^3/ha)

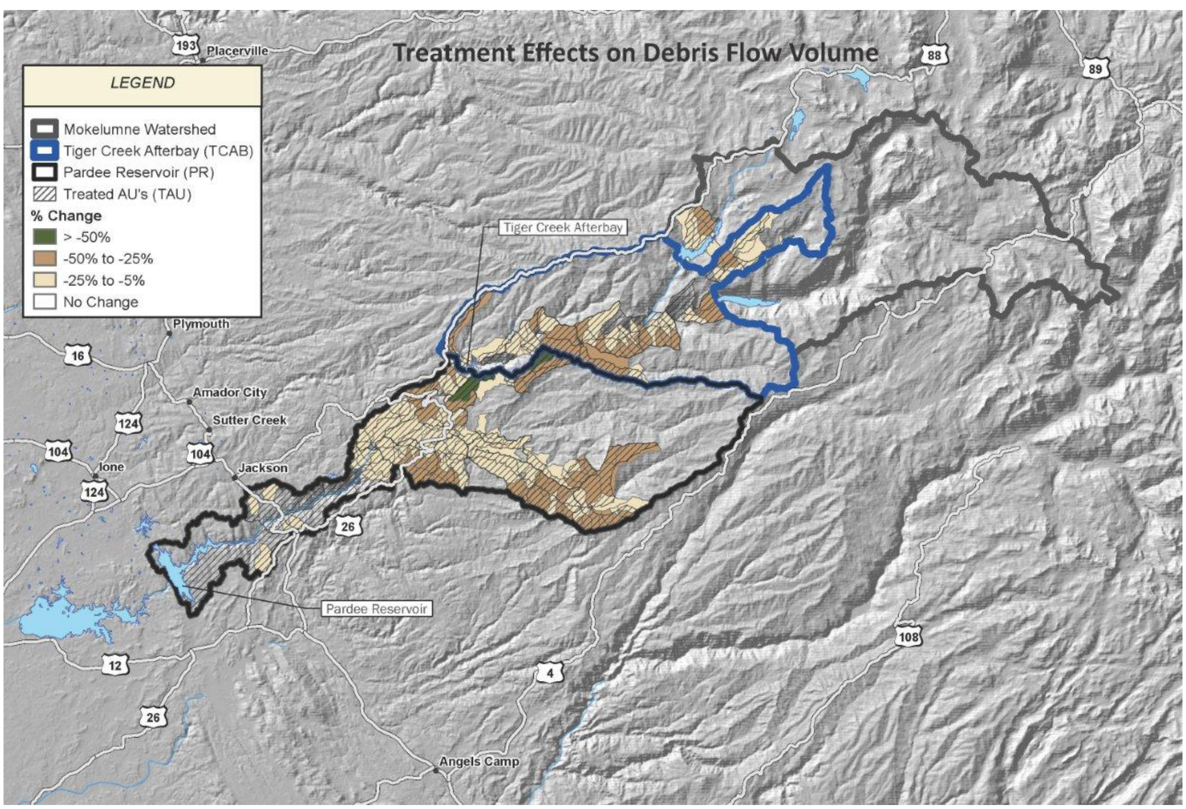


Figure 3.11: Relative change in debris flow probability as a result of treatment

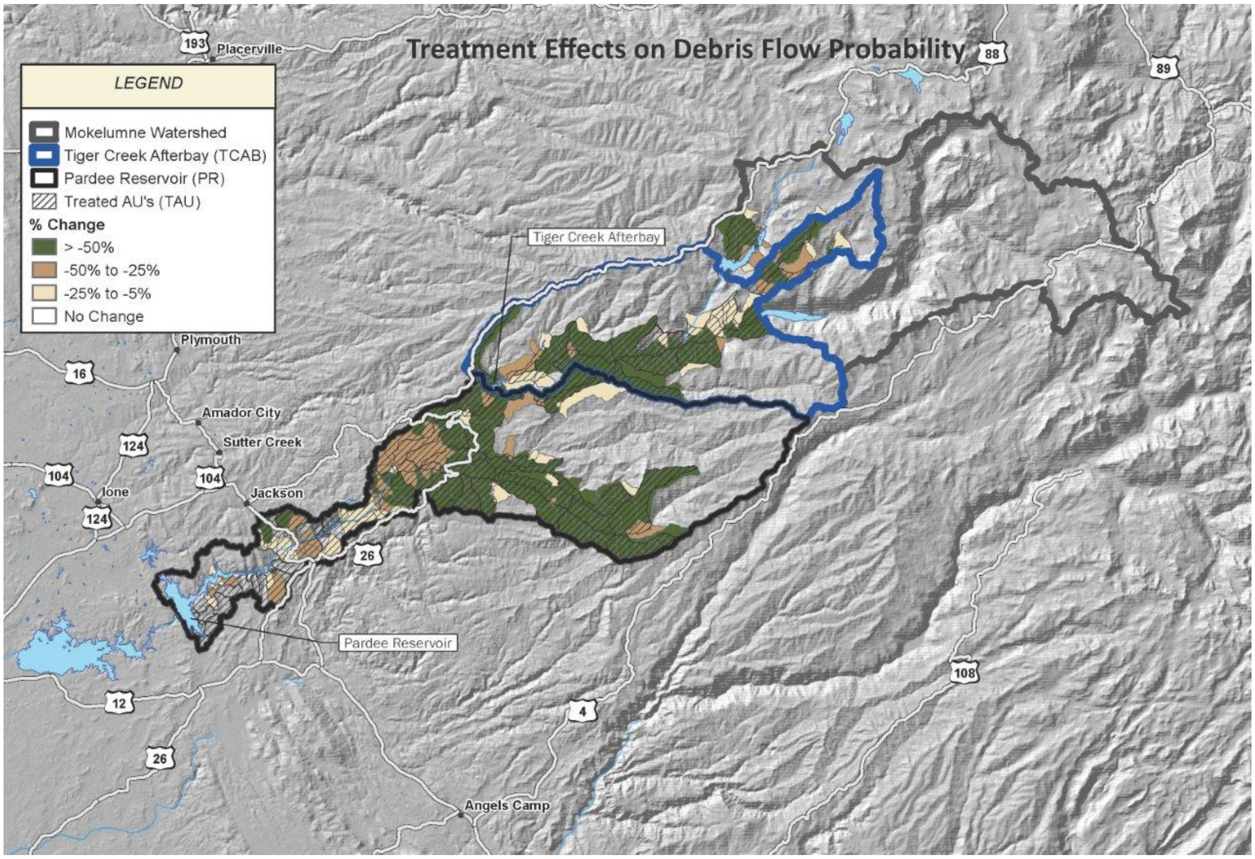


Table 3.5: Summary of key model results for PreT and PostT scenarios in the TAU

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 (50^{th}) and 90^{th} 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 (50^{th}) and 90^{th} percentile.

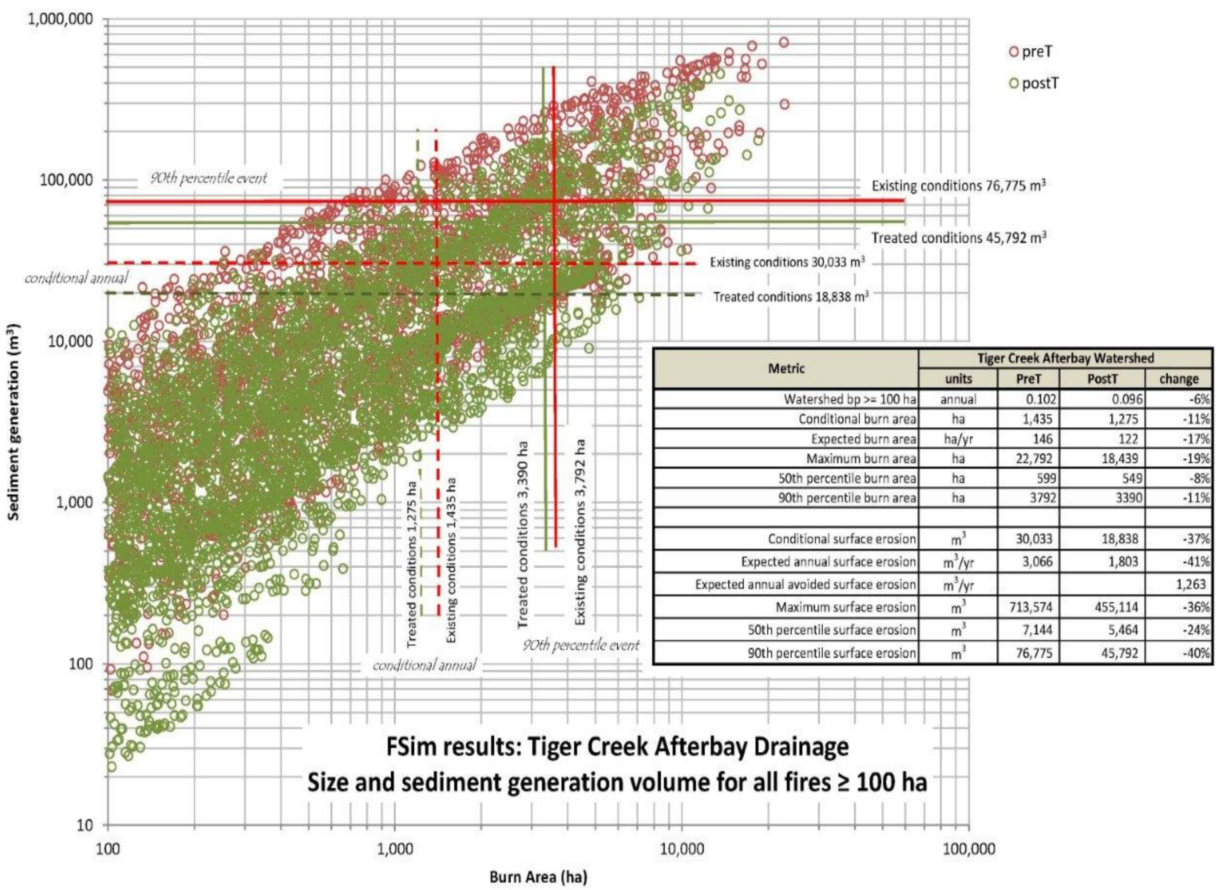
3.5.1 Tiger Creek Afterbay (TCAB)

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)

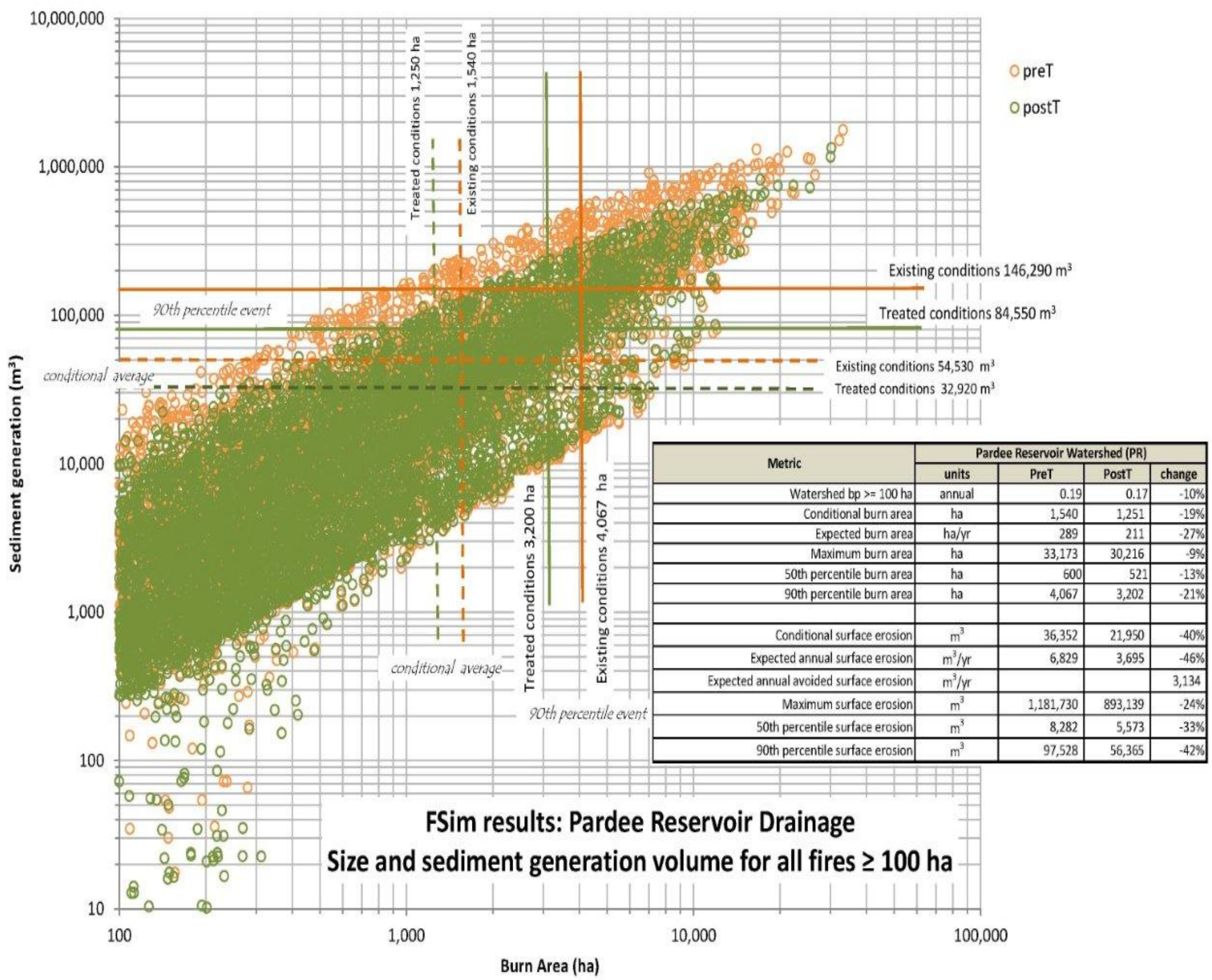


3.5.2 Pardee Reservoir (PR)

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 90^{th} 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)



Metric	Pardee Reservoir Watershed (PR)			
	units	PreT	PostT	change
Watershed bp >= 100 ha	annual	0.19	0.17	-10%
Conditional burn area	ha	1,540	1,251	-19%
Expected burn area	ha/yr	289	211	-27%
Maximum burn area	ha	33,173	30,216	-9%
50th percentile burn area	ha	600	521	-13%
90th percentile burn area	ha	4,067	3,202	-21%
Conditional surface erosion	m^3	36,352	21,950	-40%
Expected annual surface erosion	m^3/yr	6,829	3,695	-46%
Expected annual avoided surface erosion	m^3/yr			3,134
Maximum surface erosion	m^3	1,181,730	893,139	-24%
50th percentile surface erosion	m^3	8,282	5,573	-33%
90th percentile surface erosion	m^3	97,528	56,365	-42%

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.

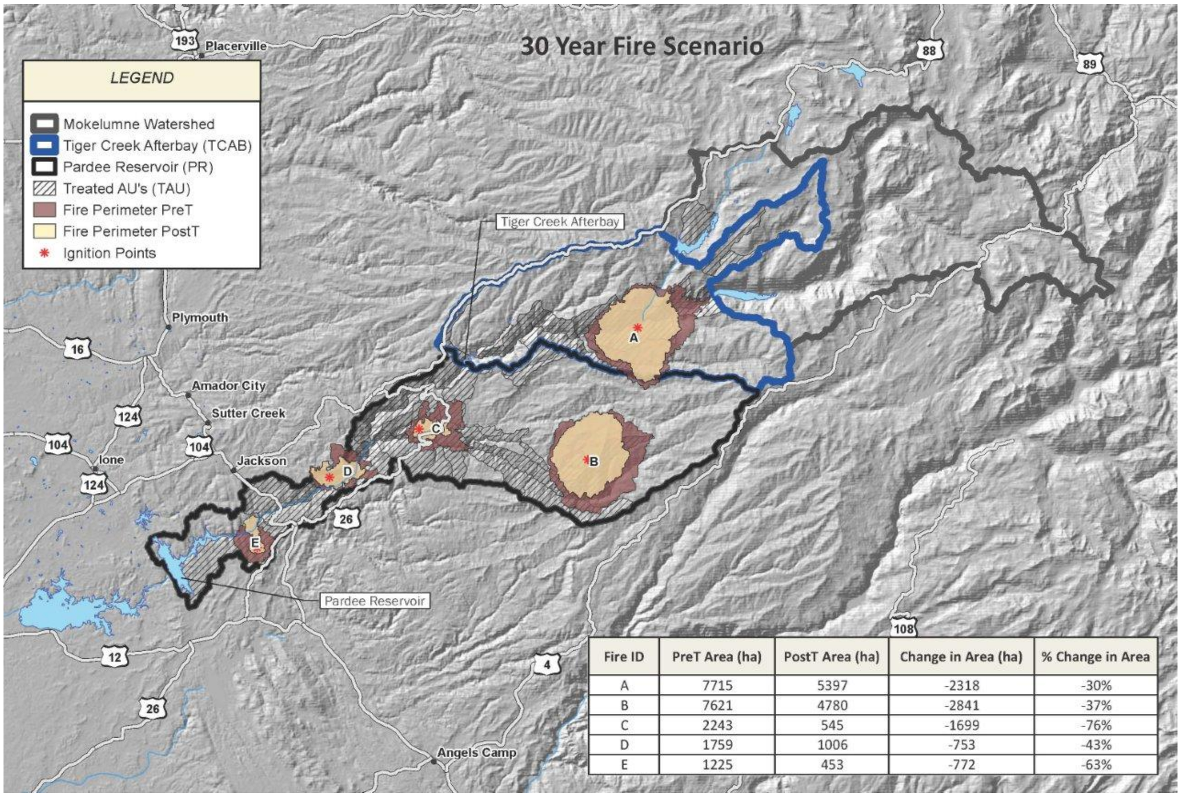
One future TCAB fire was selected and is referred to as Fire A, a 7,715-ha fire that on its own achieves the expected 20% burn area of the TCAB subwatershed. For the PR subwatershed, four fires were selected to represent a range of climate-adjusted potential fire sizes and locations: a 90th percentile 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

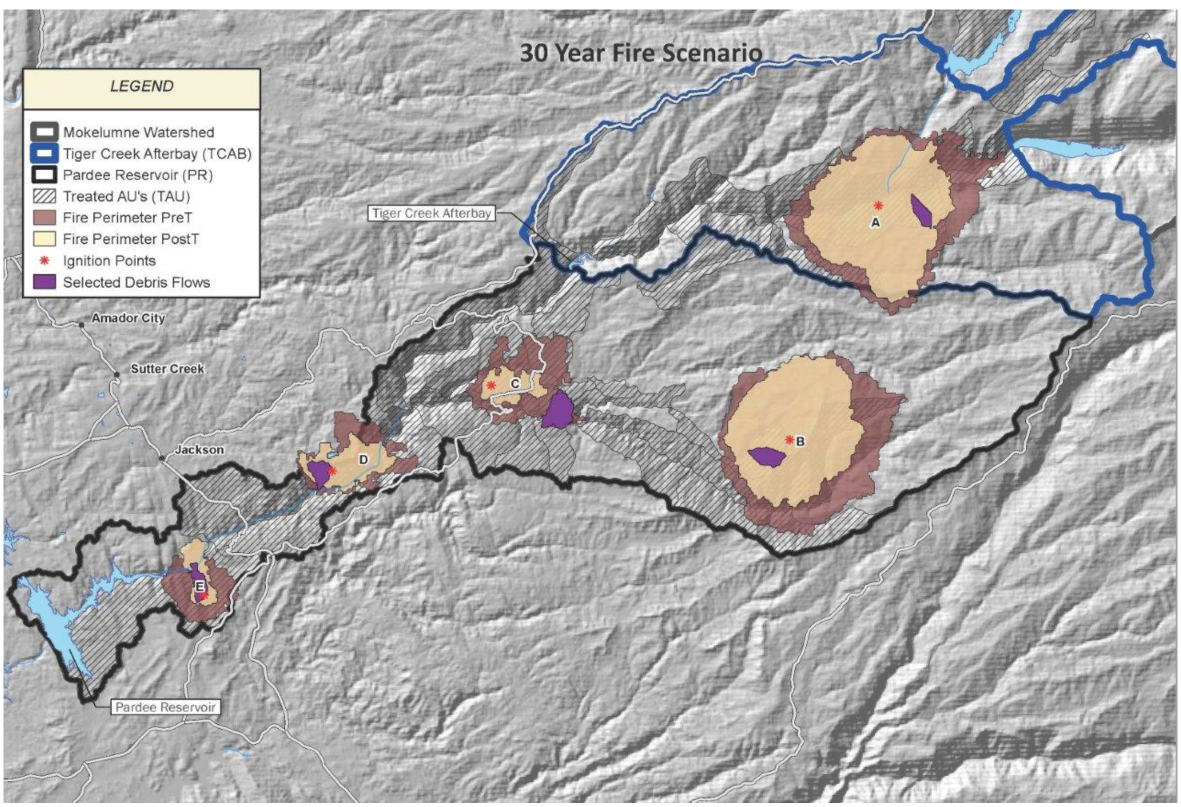
Figure 3.14 illustrates that treatments resulted in a significant reduction in burn area, from 30-76%. The fire perimeters were overlaid with the GeoWEPP model results to determine the relevant sediment volumes generated by surface erosion from these fires. Similarly, the perimeters were overlaid with 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%

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.

Surface Erosion No Fire

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%

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

Debris Flow Post Fire

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%

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

PreT 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

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

PostT Conditions

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

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

Treatment Effects

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.

[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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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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