Post-Fire Sedimentation and the Risk to Sierra Nevada Water Supply

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This Master's Project

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Chapter 1: Introduction

1.1 The Importance of Forested Areas for Water Supply

Forests throughout the world are invaluable resources not only because of the flora and fauna that they support, but also because of the ecosystem services that they provide. Ecosystem services are benefits people gain from the environment (Brauman et al. 2007). Forest ecosystem services include carbon sequestration, natural water storage, and large quantities of high-quality drinking water (Bladon et al. 2014). Healthy forests have been described as water factories that intercept precipitation, increase groundwater, slow runoff, reduce flooding, and purify water, while also providing ample habitat for wildlife (Sedell et al. 2000). As water demand continues to increase, the importance of maintaining healthy forests becomes even more crucial.

In the United States it is estimated that two-thirds of municipalities receive the majority of their drinking water supplies from forested areas (Bladon et al. 2014; Smith et al. 2011). In California, the Sierra Nevada region only accounts for about 25% of the total land area, yet 60% of the state’s developed water supply (Sierra Nevada Conservancy 2013). Economically, the region is important to the state not just for its water supply, but also because of major hydropower projects and the production of wood products (Sierra Nevada Conservancy 2013). Unfortunately, many of these forested regions are being increasingly threatened by the risk of wildfire and in turn so are the water supplies they support.

1.2 Importance of Wildfires in Forested Ecosystems

Wildfires are a natural ecosystem process and not all fires are catastrophic. Many ecosystems are adapted to fire, and fire suppression can lead to adverse consequences. Fire has been described as a “global herbivore” in that it consumes biomass and helps define species composition (Bond and Keely 2005). Frequent low intensity fires can reduce the height of dominant woody plants, reduce surface biomass, and allow small herbaceous plants with high light requirements to co-exist (Bond and Keeley 2005). In
areas where historically there were frequent fires, fire suppression can change the species
occupancy, facilitate tree invasions into grasslands, exclude small herbaceous plants,
increase the accumulation of organic matter, and create more uniform tree strands (Steel
et al. 2015). Conifer forests in southwestern North America historically had relatively
frequent, low intensity surface fires, which resulted in lower tree density and greater plant
heterogeneity (Bond and Keeley 2005). Fire suppression has increased tree density in
forests by at least an order of magnitude and shaded out much of the diversity in the
herbaceous understory (Bond and Keeley 2005). The overall increase in woody biomass
and organic matter due to suppression creates more fire fuel, which can result in larger,
more severe fires.

1.3 Wildfire Frequency, Size and Severity

Since the 1980’s there has been an increase in the number of large, more severe
wildfires throughout much of the western United States, and there is strong evidence that
this trend will continue (Miller et al. 2008; Smith et al. 2011). In the Sierra Nevada
region the increase of large, severe wildfires poses a major risk to important watersheds.
Fire regimes in a given area are defined by their pattern of frequency, season, type, and
extent in a landscape. As a results of climate change, fire seasons in the western US are
also occurring earlier and lasting longer (Bladon et al. 2014; Miller et al. 2009). Climate
change coupled with drought and human proximity to forested areas will continue to
increase the prevalence of large, more severe wildfires in forests with abundant biomass.
More severe wildfires can have more drastic effects on vegetation replacement and
greater impacts to water quality and quantity.

1.4 Wildfire Direct, Indirect Impacts and Contaminants of Concern

Wildfire impacts can be considered either direct or indirect. Direct impacts
include immediate consequences of a wildfire such as plant injury and mortality, soil
heating, organic matter fuel consumption, and smoke production (Keane 2009). First-
order direct impacts drive second-order indirect impacts, and examples of second-order
impacts include erosion, vegetative succession, and altered ecosystem processes (Keane 2009; Nyman et al. 2013). This paper will focus on the direct impacts of fire on soil properties and the indirect impacts on hydrology, erosion, and subsequent sedimentation.

Post-fire pollutants can be transported through runoff and the main contaminants of concern include sediment, nutrients (nitrogen, phosphorus, and carbon), and heavy metals. These contaminants are transported when post-fire hillslopes are exposed to rainfall and overland flow, and then subsequently erode (Figure 1, 2). Sediment inputs are problematic because they can affect the color and turbidity of water and may also transport particle-bound contaminants (Smith et al. 2011). Post-fire sediment yields can be up to three orders of magnitude greater than unburned forests (Wagenbrenner and Robichaud 2014). A sediment yield is the amount of sediment per unit area in a given time period that is removed from a watershed by overland flow (Griffiths et al. 2006). Post-fire stream increases in nitrogen, phosphorus, and dissolved organic carbon are the result of atmospheric inputs of ash during the fire, runoff containing ash after the fire, and soil erosion and remobilization of nutrients stored in the sediment (Bladon et al. 2014; Smith et al. 2011). Trace metals of concern post-fire include iron, manganese, zinc, barium, copper, aluminum, lead, and mercury (Smith et al. 2011). Other contaminants include organic carbon, cyanide, polycyclic aromatic hydrocarbons (PAHs), polychlorinated di-benzo-p-dioxins and dibenzofurans (PCDD/Fs), and polychlorinated biphenyls (PCBs). The focus of this review will be on the transport of sediment post fire, subsequent water quality issues, and management tactics.

1.5 Sediment Transport

Sediment transport from soils is largely influenced by the hydrophobicity of the soil, changes to soil properties, and the loss of vegetative and organic protective layers (Wittenberg et al. 2014). The inherent problem with addressing sediment transport post-fire is the associated ambiguity. Burned areas are not uniform and have differences in groundcover, weather, topographic characteristics, and land management practices (Shin et al. 2013). Groundcover increases infiltration and surface roughness, and reduces the loss of sediments. Post-fire sediment transport is driven largely by precipitation and is
therefore episodic (Moody et al. 2013). Additionally, basins are not generally burned in a uniform manner and are therefore spatially variable (Moody et al. 2013). Most sediment transport studies are based on small-scale fire responses and there is limited literature investigating watershed-wide sedimentation. As the prevalence of large, severe fires continues to grow, it is of utmost importance to evaluate the overall risks of sedimentation in watersheds crucial for water supplies.

In addition to addressing past sediment studies, this paper will investigate the effects of sedimentation on important watersheds in the Sierra Nevada region. The main fire that will be discussed is the Rim Fire. This fire occurred in 2013 in the Upper Tuolumne Watershed and burned 257,314 acres in the Stanislaus National Forest and Yosemite National Park (Figure 4, 5) (SFPUC 2014). It is the largest recorded fire in the history of the Sierra Nevada and the third largest fire in California’s history. The 2002 McNally Fire in Sequoia National Forest and the 2012 Bagley Fire in Shasta-Trinity National Forest will also be discussed in relation to sediment-laden flooding. Various fires in the Sierra Nevada that were followed by debris flows will also be evaluated. Figure 4 shows the Sierra Nevada region and where all the fires discussed in this paper occurred. A commonality between all these fires is they primarily occurred on national forest lands and occurred in areas that provide water resources for the state.

1.6 Land Management Post Fire

The US Forest service manages 193 million acres of public land where it is estimated that 20% of the country’s clean water supply originates, while the National Park Service has 84 million acres (Batker et al. 2013). In the Sierra Nevada, the US Forest Service manages 6.3 million acres, accounting for approximately 60% of the region (Sierra Nevada Conservancy 2013). The way these lands are managed both before and after a fire influences post-fire effects. Both the National Park Service and the US Forest Service produce Burned Area Emergency Response (BAER) reports while the fire is still burning or immediately after it is extinguished that outline post-fire assessments and treatments across federal land. These reports assess the overall risks associated with fire including risks to life and property, soil alterations, hydrologic changes, reductions in water quality, and how to respond to emergency conditions such as soil erosion and flash
flooding (Robichaud et al. 2000). These reports also include the implementation of post-fire rehabilitation measures if deemed necessary. The post-fire mitigation priorities usually emphasize immediate land management actions to rehabilitate or restore a burned landscape and focus less so on long-term management (Beschta et al. 2004).

Effective post fire management is crucial because the tactics employed can influence forest dynamics and aquatic systems for decades to centuries (Beschta et al. 2004). Beschta et al. (2004) recommends practices that protect soils (i.e., mulching), retain large trees, and help restore natural recovery processes; while discouraging seeding non-natives, livestock grazing, removal of large trees, and logging. The most controversial post-fire land management topic is by far salvage logging (McIver and Starr 2000). In the context of sedimentation, opponents argue that it enhances sediment production and erosion, while proponents argue that salvage logging can reduce future surface woody fuel loads and reduce the severity of future fires (Peterson et al. 2015). If salvage logging is done it needs to be implemented strategically so that erosion is minimized.

1.7 Key Questions

The driving question of this paper is how are large-scale, more severe wildfires in the Sierra Nevada region in California facilitating sediment transport? Additionally, this paper will also address how post-fire forest management influences sediment loadings. Forest management tactics include erosion control strategies and salvage logging.
Chapter 2: Evaluating Fire Severity

2.1 Fire Severity

Historically large wildfires were common in the US, but an era of aggressive fire suppression diminished these occurrences for several decades (Bartlett et al. 2002). Commonly, wildfires are classified as large when they exceed 10,000 hectares, or rather 24,710 acres (Keane et al. 2008). In 1905, the US Forest Service was established and early fire management policies prioritized halting all fires. In 1926, the prevailing policy for fire management aimed to eliminate all fires before they spread. In 1935, the “10 am policy” was created with the goal of extinguishing any fire exceeding ten acres by 10 am the next day. Furthermore the introduction of the Smokey the Bear campaign and his dictum “remember… only you can prevent forest fires,” helped to reinforce the common belief that all fires are harmful and should be extinguished immediately. These policies were ubiquitously accepted until the 1970’s when people began to realize the importance of fire as an ecosystem process (Pyne 1982). There is now wide recognition that fire plays an important role in overall forest health and management, but past polices have resulted in huge biomass accumulations and larger, more severe fires (Dodge 1972; Pollet and Omi 2002).

Fire or burn severity is a qualitative effect of a fire on an ecosystem, and while some components of burn severity can be measured, severity cannot be expressed as a single quantifiable measurement (Robichaud et al. 2000). Burn severity is often based on post-fire appearance of vegetation, litter, and soil and broadly defined in low, moderate, and high burn severity classes (Table 1) (Robichaud et al. 2000). Therefore, burn severity has both aboveground and belowground components and is highly dependent on the fuels available for burning (Neary et al 2005). The main concerns with high soil burn severity are the removal of the protective cover (both vegetation and litter) and heating induced changes to aggregate stability and water repellency.
Table 1- Fire Severity Classification (Robichaud et al. 2000, Hungerford 1996, DeBano et al. 1998)

<table>
<thead>
<tr>
<th>Burn Parameter</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litter</td>
<td>Scorched, Charred,</td>
<td>Consumed</td>
<td>Consumed</td>
</tr>
<tr>
<td></td>
<td>Consumed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duff</td>
<td>Intact, Surface Char</td>
<td>Deep Char, Consumed</td>
<td>Consumed</td>
</tr>
<tr>
<td>Wood Debris-Small</td>
<td>Partly Consumed, Charred</td>
<td>Consumed</td>
<td>Consumed, Deeply Charred</td>
</tr>
<tr>
<td>Woody Debris-Logs</td>
<td>Charred</td>
<td>Charred</td>
<td></td>
</tr>
<tr>
<td>Ash Color</td>
<td>Black</td>
<td>Light Colored</td>
<td>Reddish, Orange</td>
</tr>
<tr>
<td>Mineral Soil</td>
<td>Not Changed</td>
<td>Not Changed</td>
<td>Altered Structure, Porosity, etc</td>
</tr>
<tr>
<td>Soil Temp at 0.4 in</td>
<td>&lt;50°C</td>
<td>100-200°C</td>
<td>&gt;250°C</td>
</tr>
<tr>
<td>Soil Organism</td>
<td>To 10 mm</td>
<td>To 50 mm</td>
<td>To 160 mm</td>
</tr>
</tbody>
</table>

Fire intensity and fire severity are often used interchangeably, but while intensity relates to severity these concepts are not the same. Intensity is the rate at which aboveground fuel is consumed, the heat produced, and the linear rate at which a fire is spreading (Albini 1976, Alexander 1982). Fire intensity is the energy released during different fire phases and includes metrics such as combustion intensity, fireline intensity, residence time, and temperature (Keely 2009). Fuels that readily burn in short time periods have greater fire intensities than slow burning fuels (Neary et al. 2005). The duration of burning is important for the downward transfer of heat energy since often little heat is transferred downward in fast moving crown fires (Neary et al. 2005). Comparatively, fire severity can be seen as a product of the fire intensity and overall fire residence time (Neary et al. 2005). In relation to soil burn severity, the notable effects on soil are removal of groundcover, changes in soil porosity, reductions in water infiltration, and induction of water repellency.

Fire types and their respective behavior patterns influence fire severity (Table 2). Fire types are spatially and temporally variable and depend on weather, terrain, and...
vegetation. Weather factors such as humidity, wind, and lack of precipitation influences the total fuel available. Terrain features such as slope, aspect, elevation, hill-slope drainage, and landform features influence how a fire spreads. Different vegetation communities have varying structures and overall flammability which influences fire type, and fires are often a mix of fire types depending on the local conditions (Ryan 2002). Ground fires burn for hours to weeks independently of surface and crown fires in soil humic layers as well as in organic and peat soil muck mainly through smoldering (Neary et al 2005, Ryan 2002). Surface fires burn loose litter, woody debris, and understory vegetation less than two meters tall through flaming combustion (Neary et al. 2005). Prolonged surface fires can result in substantial soil heating (Hartford and Frandsen 1992). Surface fires can transition to crown fires where the fire burns the foliage above the surface fuels (i.e., the top layer of foliage on a tree) (Neary et al. 2005). Crown fires burning in the canopy of trees or shrubs are largely independent of surface fires. Crown fires typically release the most amount of energy (are the most intense) through flaming combustion, but last the shortest amount of time.

**Table 2- Fire Behavior Characteristics (Ryan 2002)**

<table>
<thead>
<tr>
<th>Fire Type</th>
<th>Dominant Combustion</th>
<th>General Description</th>
<th>Rate of spread (meters/min)</th>
<th>Flame Length (meters)</th>
<th>Fireline Intensity (kW/meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground</td>
<td>Smoldering</td>
<td>Creeping</td>
<td>0.0003 to 0.016</td>
<td>&lt;0</td>
<td>0.1 to 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Creeping</td>
<td>Active/spreading Intense/running</td>
<td>0.3 to 8.3</td>
<td>8.3 to 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passive crowning</td>
<td>Variable</td>
<td>3.0 to 10.0</td>
<td>Variable</td>
</tr>
<tr>
<td>Transition</td>
<td>Flaming</td>
<td>Active crowning, Independent crowning</td>
<td>15 to 100 up to 200</td>
<td>5.0 to 15 Up to 70</td>
<td>10,000 to 1,300,000 Up to 1,300,000</td>
</tr>
</tbody>
</table>

*Fireline intensity is the product of the fuel's heat content (kJ/kg), mass of fuel consumed (kg/m²) and the rate of spread (m/s)*
Fire severity is also influenced by fire frequency. Fire frequency is the number of fires in a given area and time period, and is thought to be inversely related to intensity (Ryan 2002, Olson 1981). Fire depends on the accumulation of both live and dead biomass and can be seen as a ‘global herbivore’ (Bond and Keely 2005). Fuel amount is often one of the main limiting factors, but when fire frequency is low fuel loads accumulate. In areas that historically had high fire frequency and low fire intensity/severity, fire suppression policies have resulted in fuel load accumulation. Thus, when these areas do burn there have been increases in fire intensity/severity (Steel et al. 2015). It is important to make the distinction between “fuel limited” fire regimes and “climate limited” fire regimes in relation to fire frequency/severity. Ecosystems with “fuel limited” fire regimes have fire seasons where the climatic conditions promote fire and the limiting factors are ignition and fuel load. In “climate limited” ecosystems there is generally an abundance of biomass but the fuel and/or atmospheric conditions are too wet (Steel et. al 2015).

California has a variety of forest types with fuel-limited and climate limited, as well as intermediary forest types. Steel et al. (2015) evaluated fire severity data from 1984-2011 in California and found that in fuel limited forests (yellow pine, mixed conifer), as the time since the last fire and fire return interval increases, so does fire severity. Fire return interval and time since last fire are inverse measurements of fire frequency. Therefore, this supports the idea that fire frequency is inversely related to severity in fuel-limited forests. Intermediate forest types (Douglas fir and mixed evergreen) also showed a similar relationship. Fire data from climate limited forest types (Red fir and Redwood) did not show a significant inverse relationship between fire frequency and fire severity.

**2.2 Monitoring Burn Severity**

Considerable effort has been put into mapping wildfire burn severity data in the United States. The Wildland Fire Leadership Council (WFLC) is responsible for implementing the National Fire Plan and Federal Wildland Fire Management Policies (http://www.fireplan.gov/). In 2006, the WFLC, with both the U.S. Geological Survey,
National Center for Earth Resources Observation and Science (EROS) and the USDA Forest Service, Remote Sensing Applications (RSAC), implemented a program to map national burn severity information (Eidenshink et al. 2007). This program is called Monitoring Trends in Burn Severity and all the data is publicly available (http://www.mtbs.gov). Fires in the western United States are mapped if they are 1000 acres or greater. The maps are created a year after the fire occurrence so that the map takes into account first-order (loss of biomass directly from the fire) and second-order effects (delayed plant mortality, plant regeneration and succession) (Eidenshink et al. 2007; Neary et al. 2005). It is important to note that these maps relate burn severity to effects on vegetation biomass in a given area and how it has been altered or disrupted by fire (Eidenshink et al. 2007).

The project uses Landsat imagery data and a Normalized Burn Ratio (NBR) to relate burn severity across a landscape with a resolution of 30 meters (Eidenshink et al. 2007). The Normalized Burn Ratio is developed based on aboveground consumption of living vegetation and litter on the surface as well as the change in the amount of bare soil compared to pre-fire conditions (Moody and Martin 2009). The spectral change in the post-fire NBR image compared to the pre-fire NBR is used to group fire areas into low, moderate, high, unburned to low, and increased greenness burn severity classes (MTBS 2005). Areas that display more vegetative cover, density, and/or productivity are mapped as areas with increased greenness. The unburned to low burn severity class represents areas that are either unburned or have 5% or less visible fire effects. In the low burn severity class, litter is often highly consumed while duff, woody debris, and newly exposed soil exhibit some post-fire change. Low vegetation (<1 meter), shrubs, and trees (1-5 meters) may exhibit significant scorch, char or consumption, but plants are generally still viable and recover quickly. The intermediate and large over-story trees in the low burn severity class may exhibit up to 25% mortality. Describing the moderate burn severity is difficult because this class exhibits features of the low and high burn severity classes (MTBS 2005). This classification is used for areas that are transitional in magnitude and/or uniformity between the low and high burn severity classes. The high burn severity class is used for areas that have fairly uniform post-fire effects across the landscape. In this class, litter is completely consumed and duff is almost all consumed.
The medium and heavy woody debris is at least partially consumed and deeply charred. Over-story trees exhibit 75% or greater mortality and new tree establishment post-fire is slow. In the high burn severity class over 50% of the burned area contains exposed soil and rock fragments.

1571 fires have been mapped in California between 1984 and 2013. Figure 1 shows the overall acreage at each burn severity class during this time period. In California and in the Sierra Nevada region, the prevalence of large, high severity fires is on the rise (Miller et al. 2009). There are sixteen fires in the MTBS database that have occurred in California since 1984 that are greater than or equal to 100,000 acres. Of those sixteen fires, thirteen of which have occurred since 2000. Three of these fires occurred in the Sierra Nevada region (1990 Campbell Fire, 2002 McNally Fire, and 2013 Rim Fire). The 1987 Stanislaus Complex Fire is missing from the MTBS database but also exceeded 100,000 acres and occurred in the Sierra Nevada region (Cal Fire 2013). Additionally in 2014, California had multiple large-scale fires such as the King Fire (97,717 acres) in the El Dorado National Forest and the Happy Camp Complex fire (134,056 acres) in the Klamath National Forest and this database does not yet include these burns (USFS 2014a; USFS 2014b). Monitoring burn severity and subsequent trends is extremely important for management purposes, since burn severity is an important indicator for potential runoff and erosion.

Figure 1. California Fires 1984-2013. Graph generated from MTBS data ([http://www.mtbs.gov](http://www.mtbs.gov)).
Chapter 3: Erosion and Sedimentation

3.1 Overland Flow and Sedimentation

Sedimentation into watersheds is a result of soil erosion, sediment transport, and sediment deposition. Erosion refers to the detachment and displacement of rock, soil or organic matter; sediment transport is the movement of these materials after the initial erosional displacement; and deposition is the halting of this movement (can be temporary or permanent). Sediment deposition occurs in surface depressions, side slopes, channel bottoms, channel banks, alluvial flats, terraces, fans, lake bottoms, and so on. Sediment includes minerals and fragment rock, clay minerals, precipitates, and organic material both suspended and deposited. The size of these particles varies greatly and their respective particle diameter ranges are listed in Table 3. Fires generally increase post-fire erosion and this process cannot be fully discussed without evaluating the hydrologic cycle and overland flow in a forested ecosystem.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Diameter Range in millimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>Silt</td>
<td>0.002-0.05</td>
</tr>
<tr>
<td>Sand</td>
<td>0.05-2.0</td>
</tr>
<tr>
<td>Gravel</td>
<td>&gt; 2.0</td>
</tr>
</tbody>
</table>

The hydrologic cycle consists of all processes and pathways that circulate water to and from the atmosphere, land, subsurface, and water bodies. Fire can impact this cycle in a watershed by changing water interception, infiltration, evapotranspiration, soil moisture content, and overland flow (Neary et al. 2005). Figure 2 shows a simplified depiction of overland flow. In an unburned forest, trees and other vegetation intercept precipitation and absorb its erosive energy. This process also reduces the amount of water reaching the forest floor because some precipitation intercepted by the vegetative canopy evaporates and returns to the atmosphere through evapotranspiration (Anderson et al. 1976). The remaining intercepted precipitation either drips off the vegetative canopy or flows down the stems to the soil surface. The organic matter on top of soil and in the soil
itself can also directly intercept precipitation not intercepted by the vegetative canopy. Water can temporarily be stored in the soil surface, ponded depressions, or held in snowpack and eventually infiltrate through the soil. After soil infiltration water either flows downward and laterally towards a stream channel by means of through-flow (Figure 2) or percolates slowly down into the groundwater. When the amount of water on the soil surface exceeds the soil’s capacity for infiltration, excess water flows off the surface as overland flow. In some undisturbed forests, the infiltration capacity of the soil can handle even the most intense rainfall events (Ice et al. 2004).

Figure 2: Overland Flow. Figure downloaded from:
http://snobear.colorado.edu/IntroHydro/geog_hydro.html

Fire can increase overland flow by reducing vegetative and soil interception, but the amount by which it increases is highly dependent on the size, intensity, and severity of the fire (Neary et al. 2005). In more severe fires where much of the vegetation is destroyed, interception and evapotranspiration are greatly reduced (Anderson et al. 1976). When interception and evapotranspiration are reduced, net precipitation reaching the soil surface increases (throughfall) (Neary et al. 2005). With more water reaching the soil’s
surface, the soil’s capacity for infiltration is met more quickly and overland flow occurs. Due to consumption of organic layers, fire can also reduce soil’s capacity for overall infiltration and reduce soil-water storage. Due to the lack of vegetation and organic layers, sediment particles in soil after a severe burn are more exposed to rain splash and overland flow, which increases erosion (Neary et al. 2005).

Figure 3 shows a simplified depiction of erosion in a burned landscape and subsequent sediment transport, deposition and storage. Sediment on exposed hillslopes erodes due to precipitation and is transported into drainages and floodplains via rills. Rills are small channels that form due to overland flow. Sediment temporarily deposited on floodplains is laterally eroded by waterways. Sediment stored in drainages can be transported through large storm events that result in sediment-laden flooding and debris flows. Once the sediment from drainages reaches alluvial fans or floodplains, this sediment can then be eroded laterally. When sediment reaches the active stream channel, it can be suspended in the water column and transported further downstream or deposited on the riverbed.
Fires can also induce soil repellency (or rather hydrophobicity). Fires that burn at hot temperatures can alter soil chemistry, creating an almost impenetrable layer for water generally at depths between 2-8 inches (DeBano 2000). This layer is formed due to the organic matter in a mineral soil being heated and then subsequently coating the mineral soil particles (DeBano 1981). The induction of the water repellency layer is intensified at temperatures between 175°C and 200°C, and organic matter is completely vaporized when temperatures exceed 370°C (DeBano 1981; Agee and Peek 1997). This impenetrable layer increases runoff and erosion in response to precipitation (Neary et al. 2005). However, this general idea should be used with caution. Doerr et al. (2006) showed that some soils have water repellency layers prior to burning and severe fires in these areas can minimize the repellency layer and increase soil infiltration.

3.2 Sediment, water quality, and water treatment

Soil erosion is said to be the leading cause of global water pollution, and sedimentation post-fire is the biggest impact on aquatic ecosystems (Noss et al. 2006; Bladon et al. 2014). Therefore, sedimentation post-fire is a major concern for those who manage downstream ecosystems. Increases in sediment yields or the amount of sediment removed per unit area in a given time period can harm aquatic life, increase turbidity, change the color of water, interfere with drinking water disinfection, fill reservoirs and so on (Smith et al. 2011). Increases in sediment transport and turbidity can inundate water treatment facilities and even temporarily shut down treatment plants as happened nine times from 1997 to 2000 in Salem, Oregon due to high sedimentation (Uhrich and Bragg 2003). High sediment loads can clog screens and intake filters at treatment plants making treatment ineffective.

 Increases in sediment yield post-fire can also greatly reduce the overall storage capacity of a reservoir. Lavine et al. 2001 evaluated sediment deposition in Los Alamos Reservoir following the Cerro Grande fire in New Mexico. The fire occurred in a mixed conifer forest and covered a large area (~43,000 acres) with 32% moderate to high burn severity, 32% low burn severity and 36% unburned upstream of the reservoir (Lavine et
al. 2001). The fire occurred in May 2000 and the reservoir was drained in June 2000. Sediment deposition from erosion pre-fire in the reservoir was determined to be ~0.009 mm/yr, while post-fire erosion rates were ~4.0 mm/year for a five year period. During the five years post-fire ~43,000 m$^3$ of sediment was deposited into the reservoir and therefore reduced the overall storage capacity of the reservoir.

Throughout the literature there is very little attention paid to the overall threat of fire to water treatment facilities. The US EPA summarized the risks as follows: infrastructure damage during the fire; loss of water quantity due to withdrawal for fighting the fire; source water quality changes; increased sediment in reservoirs; increased sediment and debris in storm water; and decreased water supply downstream (US EPA 2012).

### 3.3 Factors influencing post-fire erosion

Sediment delivery post-fire is largely influenced by rainfall intensity, burn severity, contributing area, time since burning, and soil repellency (Larsen et al. 2009). There are important relationships between these factors. Wagenbrenner and Robichaud (2014) compared sediment delivery post-fire in the interior western United States and based on contributing area, time since burning, and rainfall intensity, found that sediment yields post-fire can be up to three orders of magnitude greater than unburned areas.

Precipitation is the most important driving factor of post-fire hydrologic and erosion responses (Moody et al. 2013). Not only is the amount of precipitation on a burned area important but also the overall rainfall intensity is key. Rainfall intensity is the amount of rainfall over a given area, in a given amount of time. It has been shown that the greater the precipitation intensity the greater the post-fire hydrologic and erosion responses. Wondzell and King (2003) estimated that in many unburned forested areas, overland flow due to the soil’s infiltration rates being exceeded requires a storm event with a recurrence interval of 30 years, but infiltration rates in a burned area can be exceeded during a storm with a recurrence interval of 5 years or less. Recurrence intervals are the inverse of the probability of a rainfall event occurring in a given year, in a specific geographic area (USGS 2014). Some of the post-fire erosion effects can be
muted by overall lack of precipitation. Owens et al. (2013) assessed a severe wildfire in Fishtrap Creek watershed in central British Columbia and in the first year did not find significant increases in stream flows and suspended sediments. This was considered a muted response and attributed to the lack of winter precipitation in the first year post-fire. In the following years, precipitation increased, but the sediment flux was likely reduced because of vegetation recovery (Owens et al. 2013).

Burn severity has both aboveground and belowground consequences. Higher severity fires remove more vegetation and leaf litter, which in turn removes soil’s protective layer and exposes soil to erosion. Greater soil burn severity alters the physical and chemical properties of the soil and can reduce aggregate stability. The induction of soil water repellency can also increase overland flow and erosion. Vieira et al. (2015) found that runoff was significantly higher in burned areas compared to unburned areas, but the degree to which soil burn severity changed the post-fire runoff did not differ significantly between the soil burn severity classes (high, moderate, low). However, specific erosion amounts differed significantly compared to unburned areas and between all three-severity classes. Erosion amounts increased with increasing burn severity (high>moderate>low) (Vieira et al. 2015).

The contributing area is also a key factor because of its size, physical attributes and overall sediment availability. The hillslope of a contributing area is important because the steepness of a slope influences the movement of soil. Bare hillslopes can develop rills or small channels where water accumulates and subsequently transport sediments (Wohlgemuth and King 2003). As Wright et al. (1976) showed, post-fire erosion increases as hillslope steepness increases. Wittenberg et al. (2014) found that runoff and sediment yield not only increased on steeper slopes but also increased with higher burn severity. Sediment availability in a burned watershed is also a factor for post-fire sediment yield because if there is limited sediment availability then the overall sediment yield will be smaller.

Time since burning greatly influences the overall sediment yield in a burned area as well. As time since fire increases, overland flow and erosion decrease. This is largely attributed to the reduction in soil water repellency and the reestablishment of a vegetative
protective layer (Wondzell and King 2003). Generally post-fire erosion has been found to be the greatest in the first year.

3.4 Suspended sediment and turbidity

Overland flow and erosion in burned areas increases the amount of dissolved and suspended solids entering surface waters. Total suspended solids (TSS) consist of undissolved organic and mineral particulate matter including silt, clay, metal oxides, algae, bacteria, and fungi. TSS is generally measured in mg/L. Total dissolved solids (TDS) include dissolved metals, minerals, salts, and humic acids. Turbidity measures overall water clarity and is defined by the amount of light that is either scattered or absorbed by suspended materials. It is measured in nephelometric turbidity units (NTU) and is one of the most common means to determine water clarity and suspended sediment (Gray and Gartner 2009). Turbidity is largely influenced by suspended sediment but also can be increased by other materials suspended in the water column like ash and algae. The relationship between turbidity and sediment load depends on particle factors like size, density and shape. Discrete suspended sediment samples need to be taken over different turbidity ranges to develop the overall relationship between the two metrics. Generally there is a positive linear relationship between turbidity and total suspended sediment (Pavanelli and Bigi 2005).

Often sediment data is not collected following a fire, and when it is there is not a standardized method to quantify post-fire sedimentation in surface waters. Standardized metrics should be employed for greater data comparability, and these metrics should be employed on a more wide-scale basis. The collection of sediment data from a large burned watershed basin is complicated. In the Sierra Nevada, important forested watersheds are remote and accessibility for post-fire sediment monitoring is limited. One way to estimate post-fire sedimentation is by monitoring surface water downstream of a burned watershed. Uhrich and Bragg (2003) evaluated the use of real-time turbidity measurements to estimate continuous suspended-sediment loads and yields in Salem, Oregon. They found that suspended sediment and turbidity are positively correlated, but correlations are basin-specific and can change from year to year.
3.5 Large Scale Erosion: Debris Flows

Sedimentation post-fire cannot be fully discussed without addressing the most hazardous form of sediment movement: debris flows. As previously discussed, rainfall on burned areas has a high potential to transport large amounts of sediment through overland flow (Cannon and Gartner 2005). Debris flows pose a large hazard post-fire because they occur with very little warning and exert great force on anything in their path. Even small debris flows can damage structures, strip vegetation, block drainages, and result in injuries and fatalities (Cannon and Gartner 2005). Debris flows consist of masses of sediments with various particle size saturated with water surging downward due to gravity (Iverson 1997). The size and speed of debris flows vary, but large debris flows can exceed $10^9 \text{ m}^3$ in volume and peak flow speed can exceed 10 m/s (Iverson 1997). The two main processes driving fire-related debris flows are runoff driven erosion by overland flow and infiltration triggered mobilization of a discrete landslide mass (Cannon and Gartner 2005).

Not all burned drainages respond to heavy precipitation with debris flows, they may respond instead with sediment-laden flooding. Debris flows occur with specific combinations of basin morphology, burn severity, soil properties, and rainfall amounts. The magnitude of a debris flow depends on its mechanics, the physical properties of the hillslope, the consequences of fire on soil properties, and the nature of the precipitation event (Cannon and Gartner 2005). Debris flows can occur on unburned hillslopes when increases in pore-water pressure triggers failure of colluvium and soil stability (Cannon and Gartner 2005). Enhanced runoff post-fire can initiate flooding and debris flows even during minor rainstorms (Shakesby and Doerr 2006).
Chapter 4: Recent large, severe fires in the Sierra Nevada Region

Figure 4. Sierra Nevada Fires

Legend
- Bagley 46,000 acres
- Rim 257,314 acres
- Monally 150,700 acres
- InyoComplex (Oak) 28,448 acres
- Plute 36,249 acres
- Sierra Nevada Region

Data Source: MTBS Data Access, MTBS Project (USDA Forest Service/U.S. Geological Survey).
Available online: http://mtbs.gov/dataaccess.html

SNC Boundary: State of California Sierra Nevada Conservancy.
Available online: http://www.sierranevada.ca.gov/out-regions/map-downloads
### 4.1 Rim Fire

The Rim Fire started on August 17\textsuperscript{th}, 2013 near the confluence of Clavey and Tuolumne Rivers and 98% of the fire burned within the Upper Tuolumne Watershed (2% Merced Watershed) (Weddle and Frazier 2014). An unattended campfire ignited the fire. This was the 3\textsuperscript{rd} largest fire in California history and the largest fire in recorded history in the Sierra Nevada Mountains, burning 257,314 acres (Figure 4). Landownership within the fire perimeter is summarized in table 4.

#### Table 4. Burn Area by Ownership (Batker et al. 2013)

<table>
<thead>
<tr>
<th>Property Owner</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanislaus National Forest</td>
<td>154,530</td>
</tr>
<tr>
<td>Yosemite National Park</td>
<td>78,895</td>
</tr>
<tr>
<td>Sierra Pacific Industries</td>
<td>16,035</td>
</tr>
<tr>
<td>Other private land</td>
<td>7,725</td>
</tr>
<tr>
<td>BLM</td>
<td>129</td>
</tr>
</tbody>
</table>

Vegetation, Climate, and Geology

The fire burned across a variety of vegetation zones including alpine shrubs, wet meadows, dry meadows, grasslands, chaparral, and diverse forests of juniper, lodgepole pine, Jeffrey pine, ponderosa pine, black oak, incense cedar, gray pine, aspen, red fire, white fir, blue oak, valley oak, willow, alders, sycamores, and cottonwoods. The area within the Rim Fire perimeter is characterized by a Mediterranean climate with warm, mostly dry summers and cool, wet winters. Annual precipitation across the area is 30-50 inches per year with precipitation increasing with elevation (Weddle and Frazier 2014). At lower elevations the primary geology is composed of metamorphic rock, and higher elevations consist of Sierra granitic batholith and relic volcanic flows (Weddle and Frazier 2014).
Upper Tuolumne Watershed

The Tuolumne River is the largest tributary of the San Joaquin River, flowing for approximately 130 miles from its headwaters in the Sierra Nevada, and its flow regime is comprised of both free flowing and regulated river sections (SFPUC 2013). Clavey River, and both the North and South forks of the Tuolumne are free flowing; while flows are regulated on the main stem of the Tuolumne downstream of Hetch Hetchy Reservoir, as well as on Cherry Creek and Eleanor Creek. New Don Pedro Reservoir impounds the Tuolumne River downstream of the Rim Fire perimeter. Figure 5 shows a simplified depiction of the watershed as well as the locations of the USGS turbidity gauges and the Remote Automatic Weather Station operated by the US Forest Service on Smith Peak that will be discussed. The Upper Tuolumne is of vital importance to the overall water supply for California residents. San Francisco Public Utilities Commission diverts water out of Hetch Hetchy Reservoir, Cherry Lake, and Eleanor Lake, while Turlock Irrigation District owns and operates New Don Pedro Dam, which provides water for Turlock Irrigation District customers as well as Modesto Irrigation District.
A detailed water quality assessment of the Upper Tuolumne has not been made, but according to Weddle and Frazier (2014) water quality in the Rim Fire area has been consistently good with the occasional impairment due to natural and anthropogenic disturbances. One natural disturbance highlighted was the ‘87 Stanislaus Complex Fire that resulted in elevated turbidity after the initial storms post-fire, and overall sedimentation continued for a few years after the fire (Weddle and Frazier 2014). Road surface erosion during large storms in this area may also contribute to sediment increases and subsequent water quality impairments. The lack of actual turbidity or suspended sediment values in this report is either because these conclusions are based on visual observations and not empirical data, or this information was just not provided. In a
Federal Energy Regulatory Commission (FERC) relicensing report, Turlock Irrigation
District also characterized the water flowing into Don Pedro Reservoir as having good
overall water quality and low turbidity. The only recorded turbidity measurement in the
FERC relicensing documents was collected on August 21, 2012 above Don Pedro in the
Tuolumne River and had a value of 8.3 NTU.

**Burn Severity and Erosion Prediction**

Figure 6 shows the burn severity throughout the Rim Fire area and acreage burnt
at each severity. Based on above ground biomass approximately 20% of area in the fire
perimeter had high severity burning, 28% moderate, 32 % low severity and the rest was
low to unburned (MTBS 2014). The Rim Fire Burn Area Emergency Response
Assessment Soils Report estimated soil burn severity as follows: 7% high soil burn
severity, 37% moderate, 39% low, and the remaining soil in the fire perimeter was
unburned or had a very low soil burn severity. This report also estimated that 14% of the
burned area had a high erosion hazard rating, with Lower Cherry and Jawbone Creeks having the highest potential for erosion (USFS 2013c).

The Forest Service Water Erosion Prediction Project ERMiT model was used to predict overall erosion and sedimentation based on precipitation. The ERMiT model predicts runoff and erosion by simulating erosion processes in conjunction with evapotranspiration, infiltration, runoff, soil detachment, sediment transport, and sediment deposition processes (Robichaud et al. 2007). The model can be run with and without mitigation treatments (i.e. mulching, seeding, erosion control barriers). The estimated amount of sediment production for the entire Rim burn perimeter was based on different storm frequencies (excluded unburned/very low soil burn severity), and the expected sediment yields without mitigation treatments are summarized in table 5. These storms are defined by their recurrence intervals. A 2-year storm would have a 1 in 2 chance of recurrence in any given year (50%), a 5-year storm would have a 1 in 5 chance of recurrence (20%), and a 10-year would have a 1 in 10 chance of recurrence (10%).

Table 5. Estimated Sediment Yields for the Rim Fire (USFS 2013c)

| Estimated Sediment Yield (in tons)- No Treatment |
|-----------------|-----------------|-----------------|
| 2-Year          | 5-Year          | 10-Year         |
| 464,913         | 1,655,988       | 2,669,316       |

Post-Fire Turbidity

The BAER reports outline sediment yield risks but do not outline ways in which to actually test these models within a burned area. As previously mentioned, turbidity can be a good surrogate for suspended sediment because generally there is a positive linear relationship between the two (Lewis 1996). This analysis does not include the exact relationship between turbidity and suspended sediment because this has to be determined by taking discrete suspended sediment samples and comparing it to turbidity over a range of values. This information was not publicly available and suspended sediment samples may not have been collected. Therefore, there is some inherent error
associated with using turbidity as a proxy for increases in sedimentation, and future Rim Fire studies should more thoroughly investigate this relationship.

The Smith Peak Remote Automatic Weather Station was used to estimate precipitation. It should be noted that using only this gauge is problematic as it is located just outside the fire perimeter (figure 5) and because precipitation varies throughout the burned area. Rain gauges should be placed throughout the watershed to account for spatial and elevation differences in precipitation. Despite the potential error associated with using the Smith Peak RAWS station, it was the best available data source for hourly precipitation data. In a more complex analysis multiple rain gauges would need to be used and installed throughout the watershed in order to develop average precipitation across the burned area.

Turbidity Above Hetch Hetchy

Turbidity and discharge measurements were downloaded from the USGS National Water Information System interphase for the 11274790 USGS gauge located on the Tuolumne River above Hetch Hetchy. Turbidity measurements were taken every 15 minutes, and results are given in formazian nephelometric units (FNU). Data from 3/1/2012 to 8/16/2013 was classified as “pre-fire”, and “post-fire” data was from 10/25/2013 to 3/27/2015. This data was then binned by discharge in equal intervals every 150 cubic feet per second. Figure 7 shows the pre-fire turbidity and figure 8 shows the post-fire turbidity.

As exemplified by figures 7 and 8, there is an increase in overall turbidity measurements post-fire. The overall mean turbidity value pre-fire was 0.67 FNU with a maximum measurement of 10 FNU. Post-fire, the mean turbidity value was 1.1 FNU with a maximum value of 51 FNU.

Figure 5 illustrates how the 11274790 USGS turbidity and discharge gauges are just upstream of the fire perimeter. It is therefore problematic to assume that the increases in turbidity are a direct result of sedimentation. The increase in turbidity could be from overland flow originating in burned areas, though more likely it may be from the runoff and re-suspension of ash deposited from the fire above the gauge. It should also be noted
that only 1.8% of the Rim Fire perimeter drains into the Hetch Hetchy watershed and only 8% of this area received moderate to high soil burn severity. In the Yosemite National Park BAER report the low amounts of burn severity are attributed to a more restored fire regime and active fuel reduction in the area.

**Figure 7. Pre Rim Fire Turbidity, Above Hetch Hetchy (USGS 2015).**

![Boxplot of Pre Rim Fire Turbidity](image)

The band in each boxplot corresponds to the median; the upper and lower box lines are the 75th and 25th percentiles; and the box whiskers extend to the lower 10th percentile and the upper 90th percentile.

**Figure 8. Post Rim Fire Turbidity, Above Hetch Hetchy (USGS 2015)**

![Boxplot of Post Rim Fire Turbidity](image)

The band in each boxplot corresponds to the median; the upper and lower box lines are the 75th and 25th percentiles; and the box whiskers extend to the lower 10th percentile and the upper 90th percentile.
Wards Ferry Gage

Almost all the water that drains from the burned perimeter flows downstream into Don Pedro Reservoir. Following the Rim Fire, the USGS installed a gauge to monitor the effects of the fire on Don Pedro Reservoir with funding provided by Turlock Irrigation District, Modesto Irrigation District, and SFPUC (http://ca.water.usgs.gov/projects/2014-10.html). The main issue with analyzing the turbidity data is the dearth of pre-fire data available for comparisons, which results in unknown baseline conditions. Ideally, pre-fire data would exist or a gauge in a neighboring watershed, such as the Stanislaus to the north, would have also been installed. Unfortunately, this is not the case, but there is still value to be gained from this limited data.

Instead of comparing pre vs. post-fire turbidity, turbidity spikes at the 11285500 USGS gauge were evaluated in relationship to precipitation (Figure 5). Selected storms had total precipitation amounts of 1.0 inch or more in a 24-hour period, occurred during the first year after the fire, and had turbidity data before, during, and after the storm. One exception was the storm that occurred in July 2014. Rain data was collected from the Smith Peak Remote Area Weather Station (Latitude: 37° 48' 02", Longitude: 120° 06' 03") at an elevation of 3870 feet (Figure 5).

All of the storms presented show a general trend where precipitation is followed by a spike in turbidity at the USGS gauge. The overall turbidity time delay depends on the storm. The likely reason for the delay between precipitation and the turbidity spike is due to the burned areas being located farther upstream and the additional time it takes runoff to travel downstream. Three of the four storms showed an increase in discharge following precipitation likely due to an increase in overland flow. The storm on July 20th does not have a clear discharge spike likely because the Tuolumne is a regulated river.
Of all the storms, the January 30-31\textsuperscript{st}, 2014 storm (figure 9) events have the lowest turbidity spike which may be a result of low overall discharge since sediment can more readily settle out at lower flows. The March 3-6\textsuperscript{th}, 2014 storm (figure 10) events have the highest spike in turbidity following precipitation. March 6\textsuperscript{th} had the highest hourly total precipitation of any of the storms with the highest hourly total precipitation being 0.31 inches. The gauge also stopped working for a period of time on March 6\textsuperscript{th} possibly due to sediment over-inundation. Therefore, the overall turbidity spike may have been even higher. The storm on April 25\textsuperscript{th} (figure 11) had gradual precipitation throughout the day. The overall spike in turbidity was not as pronounced as it was during the March storms but was included because I conveniently was rafting the river during the storm. The water went from clear with obvious ash deposition on the riverbed on April 24\textsuperscript{th} to a turbid brown on April 25\textsuperscript{th} (Picture 1). The storm in July (figure 12) showed a huge turbidity spike in response to a summer thunderstorm. The storm had far less cumulative precipitation, but the overall intensity for the short period it rained likely led to a great deal of runoff and erosion. It should also be noted that during July there is obvious diurnal variation in the discharge hydrograph. This is because the Tuolumne is a regulated river and water is released in the mornings for rafting flows and hydropower generation. The time lag (~29 hours) between the precipitation and the turbidity pulse can most likely be attributed to sediment being washed into the watershed at higher elevations, then following the subsequent water shut off, sediment likely settled out, and then once the water was turned back on, the sediment was re-suspended and transported downstream.
Figure 9: Storm Series 1 (USGS 2015)

Figure 10: Storm Series 2 (USGS 2015)
Figure 11: Storm Series 3 (USGS 2015)

Figure 12 Storm Series 4 (USGS 2015)
Small Debris flows in the Rim Fire perimeter

The Forest Service noted five locations on Lumsden Road where the road was blocked or partially blocked due to small debris flows on March 3rd (DeGraff 2014). These debris flows are thought to have occurred the week before the March storms mentioned above. The storms that occurred February 26-28th, 2014 had high intensity rainfall which likely lead to the debris flows. Lumsden Road leads down to the commercial rafting put-in at Meral’s Pool just below the confluence of the South Fork of the Tuolumne River and the main stem of the Tuolumne. The storms that followed in March likely washed sediment from these debris flows into the Tuolumne River which may have contributed to the high turbidity spikes. Erosion from other burned areas also likely contributed to the high turbidity spikes. The USGS, National Weather Service, and the CA-NV River Forecast Center estimated precipitation thresholds that would trigger debris flows, rockslides, ash movement, and flash floods for the winter immediately following the Rim Fire as follows (USFS 2013b):

- 0.2” in 15 minutes
- 0.3” in 30 minutes
- 0.5” in 1 hour
- 0.9” in 3 hours
- 1.4” in 6 hours

In the BAER report the overall risk for debris flows in the burn perimeter was high due to the steep terrain, severity of the fire, and proximity to local populations (Staley 2013). Based on hourly precipitation, none of the storms presented in figures 9-12 had hourly rainfall intensities that exceeded the 0.5” in 1-hour threshold. With California being in a drought, one positive outcome may be that the overall risk of debris flows and erosion post-fire has been minimized due to the lack of precipitation. That being said, even with lower than normal annual precipitation, isolated high intensity rainfall events can still have large effects.
4.2 Sediment-laden flooding

Increases in overland flow and erosion are notable from a burned area even with small amounts of precipitation (Neary et al. 2005). The 2002 McNally Fire and 2012 Bagley Fire highlight how rain events with high intensities can have drastic effects on flooding and sedimentation.

The McNally Fire burned in the summer of 2002 in Sequoia National Forest and burned 150,700 acres (Figure 4) (Thill 2012). In November of 2002, a storm system hit the burned area and dropped approximately 20 inches of rain in a 48-hour period (based on the Johnsondale RAWS station) causing the North Fork of the Kern River to surge from 200 cubic feet per second to 35,000 cubic feet per second over night (Thill 2012). During this storm, massive amounts of sediment and debris were deposited throughout the watershed, including downstream into Lake Isabella. The overall sediment and debris volume was estimated at 50 million cubic yards and resulted in the Kern River running dark brown for a year after the fire (Bonnicksen 2008). The California Water Service Company reported a 500% increase in sediment, which resulted in intake valves being clogged and the temporary closing of power plants (Bonnicksen 2008). Additionally, fish hatcheries were shut down and massive fish kills were reported.

The Bagley Fire burned 46,000 acres in late summer 2012 south of McCloud, CA in the Shasta-Trinity National Forest (USFS 2013a). This fire occurred in the Eastern Klamath Mountains rather than the Sierra Nevada, but was included to highlight sediment-laden flooding and sedimentation in an important watershed in California. Between November 29\textsuperscript{th} and December 2\textsuperscript{nd} 2012 two storms hit the burned area and dropped approximately 15-22 inches of rain (USFS 2013a). At the McCloud RAWS station just to the north, the normal average annual precipitation is 47.61 inches. In only a few days, these storms dropped roughly 1/3 to 1/2 of the normal average precipitation for the year. The main stream with notable sediment transport was Squaw Creek. Stream reaches were inundated with sediment and it was estimated based on aerial photos that seven miles of the creek stored sediment from the storms with an average thickness of 0.5 meters (USFS 2013a). Based on USGS flooding modeling regression equations, Squaw Creek rose to over 15,000 cubic feet per second (USFS 2013a). Squaw Creek also remained turbid for months following the event. Squaw Creek as well as the McCloud
River delivered a large amount of sediment originating in the burn perimeter to Lake Shasta causing the lake to be turbid. The overall sediment budget from the storm has not yet been calculated, but one is being developed according to the interim report (USFS 2013a).

### 4.3 Debris Flows

Occurrence of debris flows in the Sierra Nevada is associated with intense rainfall, rain-on-snow events, and rapid snowmelt (DeGraff 1994). On July 12, 2008, two major debris flows occurred in the southern Sierra Nevada in two recently burned watersheds. The debris flow generated in the Oak Creek watershed and the area where it originated had been burned in July 2007 during the Inyo Complex wildfire (DeGraff et al. 2011). The other debris flow was south of Oak Creek and was generated in the Erskine Creek watershed, eventually moving into the Kern River (DeGraff et al. 2011). 14 days prior to the Erskine Creek debris flow, the area where the debris flow occurred burned in the Piute wildfire. The events were triggered by thunderstorms. At the Oak Creek debris flow location, rainfall intensities are believed to have reached 25.4-31.8 mm/hr with a total rainfall amount believed to be 25.4-38.1 mm (DeGraff et al. 2011). At a RAWS weather station near the Erskine debris flow, rainfall intensities were calculated as between 16.2-20.4 mm/hr (DeGraff et al. 2011). This station was not directly within the central part of the storm, where the debris flow was thought to have occurred. Thus, the rainfall intensity in the debris flow area may have been higher.

Both debris flows transported massive volumes of sediment. The overall volume of the Oak Creek debris flow was estimated as 1.56 million m$^3$ (DeGraff et al. 2011). Since Erskine Creek debris flow dispersed into the Kern River, the volume of this debris flow is unknown, but thought to be similar to the Oak Creek debris flow sediment volume (DeGraff et al. 2011). Prior to these debris flows, the largest recent debris flow in the Sierra Nevada, the Sourgrass debris flow in 1997, transported a sediment volume of 146,000 m$^3$, so the debris flows that occurred in July 2008 were several degrees of magnitude larger (DeGraff 1994). The occurrence of these debris flows after a fire poses
danger to overall human life and property, water storage, water quality, and water infrastructure.

On July 21, 2008 the Bakersfield Californian reported that a treatment plant owned by California Water Service Company was still inoperable because the facility could not handle the sediment loads following the Erskine Creek debris flow. Furthermore, two other facilities had to switch to using groundwater stores to supply water. Some farmers stopped using the river water as well because the increased sediment load could clog their drip irrigation (Galuso and Shepard 2008).

Chapter 5: Land Management Post Fire

5.1 Land Management Goals

The main goals for managing post-fire landscapes include returning the burned area to its natural state; reducing erosion and flooding; and modifying the frequency and severity of future fires (Chen et al. 2013). As previously mentioned, Burn Area Emergency Response reports are generated on federal lands while the fire is still burning or immediately after it is extinguished and include the implementation of post-fire rehabilitation measures, if deemed necessary (Robichaud et al. 2000). The underlying task of public management agencies is to use the “best available” science to help inform decision-making and to uphold environmental protection policies (Chen et al. 2013; Sullivan et al. 2006). Key legislation includes the Endangered Species Act, the Clean Water Act, and the National Forest Management Act (Sullivan et al. 2006). There are differences in opinions regarding the interpretation of best available science when it comes to post-fire management (Sullivan et al. 2006). There is widespread disagreement over the effectiveness of various treatments and whether human intervention helps or hinders landscape rehabilitation (Beschta et al. 2004). The main post-fire land management actions that will be discussed in the context of sedimentation are erosion controls and salvage logging.
5.2 Erosion Control

Accelerated erosion is a pervasive concern among land managers, but the overall strategies employed have been met with mixed results. Wohglemuth (2003) evaluated the effectiveness of seeding, mechanical treatment (side slope stabilization, contour trenching, channel stabilization), the use of soil flocculating agent (polyacrylamide, a polymer added to bind and stabilize soil particles), and in stream FlowCheck™ log erosion barriers in the San Dimas Experimental Forest in the San Gabriel Mountains near Los Angeles. Seeding was found to be ineffective with no apparent effect on re-vegetation or the reduction of long-term sediment fluxes (Wohglemuth 2003). Side slope stabilization (hand-rowed vertical contours with planted barley), contour trenches (insloped horizontal platforms cut into the hillslope with a bulldozer), and channel stabilization (small gravity dams built with soil cement) reduced sediment yield by 65%, 60%, and 35%, respectively, compared to untreated controls. The extensive rilling and substantial runoff from the use of polyacrylamide to aggregate soil particles indicated this method was ineffective at reducing sediment yields. FlowCheck™ log structures reduced sediment yields by 68% compared to the controls. The mechanical treatments and the FlowCheck™ log structures showed promise for reducing sediment yields post-fire, but these treatments are expensive and labor intensive (Wohglemuth 2003).

Wohglemuth and Robichaud (2006) evaluated the effectiveness of mulching both with straw and a hydromulch in the western United States. Mulching can be defined as the application of wet or dry materials to provide ground cover for bare soils subject to erosion. Hydromulch is a mixture of water, fiber mulch, and a tackifier (i.e., chemical compound added to increase mulch adhesion) and can also include seed, fertilizer, or soil stabilizing polymers. The application of straw was the cheapest (hand applied cost per acre: $500, aerially applied with a helicopter cost per acre: $750), but while it seemed to show some reduction in post fire erosion it was also subject to removal and redistribution by wind (Wohglemuth and Robichaud 2006). The application of an aerial hydromulch had the most pronounced effects on reducing erosion but was estimated to cost $2,000 per acre (Wohglemuth and Robichaud 2006).

In a follow-up study Robichaud et al. (2013) tested the effectiveness of wheat strand mulch, wood strand mulch, and hydromulch following the Hayman Fire in
Colorado, the Hot Creek Fire and Myrtle Creek Fire in Idaho, and the School Fire in Washington. In the first year post-fire, wood strand mulches reduced annual sediment by 79% and 96% and continued to reduce sediment in subsequent years. Wheat strand mulch showed a 97-99% reduction in sediment yields during the first year post-fire at two of four fires where it was tested, but only reduced sediment in subsequent years at one of the fires. Hydromulch did not reduce sediment yields in any of the treatment areas (Robichaud et al. 2013). The authors attributed the reductions in sediment yields to an increase in total cover due to the mulches and the increases in litter and vegetation.

Robichaud et al. (2000) evaluated the effectiveness of post-fire treatments from 46 fires throughout California, Oregon, and Idaho. Once again the results were mixed. Furthermore, measuring erosion is time-consuming and expensive, so many treatments recommended in BAER reports are conducted without evaluating their overall effectiveness. Additionally, certain treatments such as seeding are questioned due to limited effectiveness and the potential competition it introduces with the natural re-establishment of vegetation from the seed bank or from neighboring areas. The geographic area in which a treatment is applied may influence its effectiveness. For instance, treatments effective in southern California may be ineffective in northern California due to differences in terrains, precipitation, and so on. There is no straightforward answer on the best method to prevent erosion, and more studies are needed to find more effective treatments.

5.3 Salvage Logging

Salvage logging is by far the most contentious topic in post-fire management, and national forest plans to salvage log are often legally challenged (Robichaud et al. 2011). Salvage logging is defined as the removal of trees from a forested area after a disturbance such as wildfire. Timber removal can be complete removal of all trees or partial removal of some trees, and may include strictly dead trees or both live and dead trees. In conifer forests, salvage logging is then generally followed by the re-plantation of conifer seedlings in order to reestablish the tree stand. On national forest land the prevailing policy has been to harvest burned timber as quickly as possible to retain some of the
economic value. Delays in salvage logging can result in the loss of tree value (generally estimated as within 3-5 years after a fire) due to decomposition (McIver and Starr 2000). The US Forest Service utilizes salvage logging as a means to offset their budget and recover some of the costs of fighting a fire. Salvage logging may also indirectly contribute to the ecological recovery of a burned area by generating funds for restoration (Lindemayer et al. 2004). Therefore, there is financial incentive for the Forest Service to allow salvage logging.

Much of the controversy surrounding salvage logging in national forests revolves around the difference between salvage logging and logging in unburned areas (Beschta et al. 1995). Salvage logging may occur in areas typically ineligible for logging, may exceed the sales and quantities allowed for logging operations in unburned areas, and may be exempt from National Forest Management Standards aimed at protecting soils and downstream water quality (Beschta et al. 1995). In unburned forests, logging operations have the potential to increase runoff and erosion by removing ground cover and disturbing the soil, but the degree of these effects depends on site conditions and the type of logging (McIver and Starr 2000). In severely burned landscapes, overland flow and erosion increase due to reductions in vegetative interception and evapotranspiration, more exposed bare soil, and increases in water repellency layers. Salvage logging has the potential to exacerbate erosion and overland flow due to greater soil disturbance and ground cover reductions (Peterson et al. 2009). Similarly to burned, unlogged areas, there is a great deal of uncertainty in the amount of sedimentation that occurs post-salvage logging because it is largely dependent on the magnitude, frequency, and timing of subsequent rain events (Robichaud et al. 2011). Additionally, there is also variation in local site conditions, harvest method, time of harvest, and magnitude of timber removal. Some of the local site conditions that create variability include the live/dead vegetation present, soil erodibility, runoff potential, slope steepness, burn severity, erosion hazards from roads, and burn heterogeneity across a landscape (McIver and Starr 2000).

Opponents and proponents of salvage logging have competing objectives. Opponents tend to highlight the ecological damage of salvage logging, while proponents largely highlight the economic benefits. The main arguments of opponents are that salvage logging removes ecologically valuable logs and snags, damages soils, alters
hydrology, increases sediment transport, increases fire risk, and impedes ecological recovery (McIver and Starr 2000). Opponents argue that salvage logging undermines the post-fire mitigation strategies to reduce soil erosion by exposing vulnerable soils to greater disturbance (e.g., compaction, erosion) (Karr et al. 2004). Many opponents also argue that burned areas should be allowed to recovery naturally without human intervention (Karr et al. 2004). Proponents of salvage logging argue that salvage logging reduces the fuel loadings for future fires by removing dead trees, allows economic recovery of a resource, and accelerates the re-establishment of trees (McIver and Starr 2000). Some proponents have even tried to establish the benefits ground-based equipment can have on reducing the water repellency layer through disturbance in burned soils.

Despite being a common practice for a long time, research devoted to the effects of salvage logging on sedimentation has been somewhat sparse until recently (Robichaud et al. 2011). Wagenbrenner et al. (2015) evaluated the impacts of ground-based logging equipment on sediment production following severe fires in Colorado. They found that salvage logging increases soil compaction, decreases vegetative cover, increases sediment production, and delays vegetative and soil recovery. Ground-based logging operations generally fell trees, then bunch 2-8 trees together, and then use a skidder to lift one end of the bunch to drag them to a truck. While the feller-buncher and skidder are part of the same process, this study subdivided the experimental plots into separate feller-buncher and skidder plots. Compared to the control sites, the skidder plots had 10-100 times the sediment production and slower vegetative regrowth (Wagenbrenner et al. 2015). The feller-buncher plots had 10-30% the amount of sediment production compared to the skidder plots, but had similar slow vegetative regrowth. The increases in erosion were attributed to soil compaction and the lack of vegetative re-growth (Wagenbrenner et al. 2015). The overall increase in erosion due to logging operations suggests that if salvage logging is to occur, erosion mitigation strategies need to be employed.

Another focus of recent studies has been to evaluate the effects of salvage logging on future fires. Dunn and Bailey (2015) evaluated the potential for salvage logging to reduce post-fire fuel loading in the eastern Cascades in Oregon and found that salvage logging increased surface woody fuel loadings by 160-237% above the maximum.
loadings in un-manipulated stands. However, Peterson et al. (2015) found that post-fire logging may initially increase surface woody fuel loads in dry coniferous forests, but as time progresses logging subsequently reduces woody debris compared to unlogged areas. In unlogged areas surface woody fuels were low initially, reached their peak 10-20 years after the wildfire, and then declined after 39 years post-fire. In logged areas, small (0.7-2.5 cm) and medium (2.6-7.6 cm) diameter woody debris were higher than unlogged areas 5 to 7 years after the wildfire, however, approximately 12 to 23 years after the fire small woody debris and medium woody debris in logged areas were reduced compared to unlogged areas. Logging also reduced large diameter fuel loadings compared to unlogged areas 6 to 39 years after a wildfire. Despite seemingly different results, these studies highlight the need to further evaluate the effects of salvage logging on fuel loadings immediately after a fire and over time.

Forest regeneration and the severity of future fires is another topic of debate in regards to salvage logging. The conventional practice has been to salvage log and then replant uniform conifer tree stands in order to expedite forest recovery (McGinnis et al. 2010). When large stand-replacing fires occur in the Sierra Nevada, shrubs succeed conifer regeneration and may dominate until conifers shade them out (McGinnis et al. 2010). Many opponents argue that salvage logging and replanting uniform conifer stands impedes natural conifer regeneration. Donato et al. (2006) evaluated conifer regeneration at high burn severity sites that were logged and unlogged following the 2002 Biscuit Fire in southwest Oregon. Unlogged sites had conifer seedling densities of 767 seedlings per hectare, while logged sites had an overall reduction in natural regeneration with 224 seedlings per hectare (Donato et al. 2006). In response to this study, Newton et al. (2006) argued that the performance of planted seedlings can exceed natural regeneration. The high density at which conifer stands are replanted has also been questioned due to the potential for future fire fuel loadings. Thompson et al. (2007) compared burn severity in southwest Oregon that burned in the 1987 Silver Fire and re-burned in the 2002 Biscuit Fire. Specifically, they evaluated sites that were salvage logged and then replanted with conifers and found that these areas tended to re-burn at higher severities compared to unmanaged areas (Thompson et al. 2007). Their results suggest that replanting uniform conifer plantations after salvage logging can increase future fire severity.
Many opponents have come to recognize that salvage logging is inevitable so measures to minimize the negative implications of salvage logging should be employed. Beschta et al. (2004) suggested that salvage logging should be prohibited on sensitive sites including riparian areas, moderate or severely burned areas, fragile soils, steep slopes, and road-less areas, and the method of timber removal should be chosen carefully. Specifically, ground-based logging equipment should be banned in areas where it will accelerate erosion (Beschta et al. 2004). Construction of new roads for salvage logging should be prohibited so runoff and erosion is not increased further in burned areas, since the road network required for ground-based equipment can facilitate post-fire erosion. Mean road density in the national forests of the Sierra Nevada is estimated at approximately 1.7 miles per square mile of forest, and any new roads will facilitate more erosion (Karr et al. 2004). Alternatives to ground-based logging include helicopter logging and skyline or cable logging where harvested logs are transported on a suspended cable.

5.4 Rim Fire Revisited

Following the Rim Fire there was a lot of controversy associated with the Stanislaus National Forest Service plans to salvage log. United States Representative Tom McClintock introduced a bill known as the Rim Fire Emergency Salvage Act to expedite the salvage logging process and bypass environmental review and administrative appeal (McClintock Letter 2014). McClintock’s sentiments focused on regaining the economic value of the dead trees to offset the Rim Fire catastrophe, but time was of the essence since waiting would allow dead trees to begin to decay and lose their economic value. There were large outcries from salvage logging opponents and this bill was not successful in the sense that the US Forest Service had to complete the environmental review process. In response to the preliminary USFS Rim Fire Recovery Project plan, the California Chaparral Institute refuted the claims that salvage logging would aid ecological recovery and was repeating the mistakes made in the ‘87 Stanislaus Complex Fire.

As figure 13 shows, the Upper Tuolumne Watershed has a long history of fire. Parallels between the ‘87 Stanislaus Complex Fire (146,000 acres) and the Rim Fire have
been drawn largely because both were large, severe fires and the Rim Fire re-burned a lot of the ‘87 Stanislaus Complex Fire area. Additionally, salvage logging has played a big role in post-fire management for both fires. Chou et al. (1994a) evaluated the effects of sedimentation post salvage logging after the ‘87 Stanislaus Complex fires by installing and monitoring sediment dams below salvage logging locations. The two treatment types included cable logging for slopes greater than 35% and tractor logging for slopes less than 25%. Chou et al. (1994a) concluded that their findings showed no effect on sedimentation from ground-based salvage logging on gentle slopes. In a follow up report, Chou et al. (1994b) found that cable logging on steeper slopes increased sedimentation. It should be noted that from 1987-1992 California was in a drought (Roos 1992). Therefore, some of the overall effects of salvage logging may have been muted by the lack of precipitation and runoff.

Figure 13: Upper Tuolumne Fire History (MTBS 2014; Harlow 2014)

The Stanislaus National Forest finalized their plans to salvage log on August 27, 2014. The final plan included salvage logging on approximately 33,081 acres over a five year period (USFS 2014c). Figure 14 shows the salvage logging locations on Forest Service land throughout the Rim Fire perimeter. Not surprisingly, these salvage logging locations occur in high burn severity areas where the concentration of dead trees is the
highest. Salvage logging at these sites is restricted to only dead trees unless live trees pose a road hazard (USFS 2014c). In addition to having the greatest concentration of dead trees, these areas are also the most sensitive to erosion due to the loss of vegetative cover and greater amounts of soil disturbance (Beschta et al. 2004). As shown by figure 15, most of the salvage logging locations also occur in areas with high runoff. The Soil Survey Staff at the Natural Resources Conservation Service determined these runoff classes. The combination of high runoff classes, fire effects on vegetative cover and soil disturbance, and salvage logging has the potential to facilitate greater amounts of sediment transport from these areas. The construction of new permanent roads was also up for debate during the review of the Rim Fire salvage logging plans (California Chaparral Institute 2014). Figure 16 shows the erosion hazards associated with roads and trails in this area, and it is readily apparent that the vast majority of the area has high road erosion potential. The construction of permanent new roads was not allowed in the final salvage logging plans, but this did not exclude the creation of temporary roads. Therefore, temporary roads and existing roads have a high potential to increase erosion in this area especially because the ground-based heavy machinery necessary for logging increases soil compaction and road erosion. Figure 17 shows the relative slope of the areas being logged in Stanislaus National Forest. Most of these locations have slopes that were considered gentle (<25%) by Chou et al. (1994a). Since steeper slopes help facilitate more sediment transport, more gentle sloped salvage locations may minimize at least some of the sediment transport. All the salvage logging figures discussed also show the proximity of the salvage logging locations to surface waters. Despite the recommendation of Beschta et al. (2004) to avoid riparian areas, some of these locations coincide with close proximity to surface waters. Between high burn severity, high runoff classes, high road erosion hazards, and proximity to surface waters, salvage logging on burned areas in the Stanislaus National Forest has a high potential to facilitate greater amounts of downstream sediment transport. However, another similarity between the ’87 Stanislaus Complex Fires and the Rim Fire is that before and after both fires California has been in a state of drought. This state of drought may help reduce overall sedimentation post-salvage logging due to limited precipitation.
Figure 14 Salvage Logging Locations and Burn Severity (Bardley 2014; MTBS 2014; Soil Survey Staff)

Figure 15 Runoff Classes (Bardley 2014; MTBS 2014; Soil Survey Staff)
Figure 16 Road Erosion Hazards (Bardley 2014; MTBS 2014; Soil Survey Staff)

Figure 17 Average Slopes (Bardley 2014; MTBS 2014; Soil Survey Staff)
Plans for reforestation of the Rim Fire logged locations are set to begin in 2016. Some have argued that the reforestation that occurred following the ’87 Stanislaus Complex Fire resulted in high density conifer stands that added to the overall fuel loading and severity of the Rim Fire (California Chaparral Institute 2014). While this argument needs further analysis, it is important to evaluate and potentially use the knowledge gained to adapt the Stanislaus National Forest reforestation plan.

Chapter 6 Conclusions/Recommendations

Large, severe fires will continue to threaten important watersheds in the Sierra Nevada. The goal of this was paper was to evaluate how these large fires facilitate sediment transport and the risks they pose to water supply. An additional focus of this paper was to determine how post-fire forest management can influence sediment loading.

Erosion and sedimentation are inevitable post-fire processes that can be several orders of magnitude greater than unburned conditions (Wagenbrenner and Robichaud 2014). Fire increases erosion and sedimentation by removing soil’s vegetative and organic protective layers, changing soil properties, and inducing soil water repellency (Wittenberg et al. 2014). Sediment delivery is driven by precipitation and largely influenced by rainfall intensity, burn severity, contributing area, time since burning, and soil repellency (Larsen et al. 2009). The predicted increase of large, severe fires within important Sierra Nevada watersheds and subsequent increases in sedimentation are putting California’s water supply at risk due to degraded water quality, threats to infrastructure, and reductions in reservoir capacity.

Trying to evaluate recent large, severe fires in the Sierra Nevada proved to be quite challenging. The region has evidence of post-fire sedimentation and documented sediment-laden flooding and debris flows, but there are huge data gaps in baseline data and very limited post-fire sediment monitoring. The US Forest Service Burn Area Emergency Response reports model the overall erosion risks and hypothetical sediment yields, but these models need more empirical validation. Unfortunately, collecting
sediment data is time intensive and access to remote burned locations in the Sierra Nevada is limited. Therefore, we need another means to evaluate post-fire sedimentation.

One solution is to increase the network of USGS turbidity gauges throughout Sierra Nevada watersheds. Monitoring turbidity is one of the most cost-effective ways to evaluate sediment fluctuations once the suspended sediment-turbidity relationship is determined. USGS has 492 surface-water gauges throughout California that collect and transmit data to USGS every hour. Only 48 of these gauging stations currently collect turbidity, and of those 48, only 7 are located in Sierra Nevada watersheds. The installation of turbidity gauges should not just occur in response to a fire, but rather should be installed before burn events occur so that baseline conditions can be established. Furthermore, the use of turbidity gauges will aid in comparability between important watersheds throughout the region. Overall, prioritizing an expanded turbidity gauge network is one of the most cost-effective ways to furthering our understanding of post-fire sediment transport.

Another focus of this paper was evaluating how post-fire forest management influences sediment transport. BAER reports recommend extensive erosion control measures that are costly. These erosion control measures had varying levels of effectiveness and throughout the literature there was not an identifiable method that worked best at reducing erosion. Additionally, what works in one area, may not work in another. Erosion control will continue to be important for post-fire management so more studies that evaluate these measures in specific areas should be employed, and new erosion control strategies should be developed. Salvage logging was also evaluated in regards to post-fire management because of the potential for this practice to enhance sediment transport. Salvage logging enhances soil disturbance and removes ground cover, which in turn facilitates greater overland flow and erosion (Peterson et al. 2009). On national forest lands, the US Forest Service has a financial incentive to continue salvage logging because it offsets the costs of fighting fires. Since this practice will likely continue, measures such as avoiding riparian areas, fragile soils, and steep slopes should be employed to reduce erosion.

Maintaining healthy forests in the Sierra Nevada is an integral part of protecting California’s water supplies. The combination of overgrown forests, prolonged droughts,
climate change and human proximity to forests has increased the prevalence of large, severe fires (Bladon et al. 2014). Projected warmer temperatures and dryer conditions will continue to magnify the negative implications of wildfires. Therefore, it is imperative that forests are managed more effectively before catastrophic fires (i.e., prescribed burning, allowing natural fires to burn, and mechanical thinning) and after these fires. Even with more effective management, Sierra Nevada forests and the water supplies that they support are in peril. Moving forward, forest managers, water managers, and California residents need to recognize the importance of developing a greater understanding of the wildfire, forest health, and water supply relationship because the significance of their interconnectedness will continue to grow.
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