Bren School of Environmental Science & Management
University of California, Santa Barbara

Post-Fire Sedimentation and Flood Risk Potential in the Mission Creek Watershed of Santa Barbara

A Group Project submitted in partial satisfaction of the requirements for the degree of
Master's in Environmental Science and Management

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

Thomas Dunne, Advisor

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ABSTRACT

Runoff and erosion rates rise dramatically in the rainy seasons following wildfire, increasing the risk of destructive floods, sediment accumulation, and debris flows. Watershed assessments are typically performed post-fire, but risk quantification and determination of mitigation treatments are limited when a fire occurs immediately before the rainy season. In highly vulnerable areas, such as Mission Creek watershed in California, pre-fire analysis of post-fire risk is warranted. This study examined potential post-fire runoff and erosion risk by simulating the effects of fire on upper Mission Creek watershed. The project utilized field observations of an analogous burned watershed, spatially explicit data on watershed characteristics, historic rainfall and runoff measurements, and accepted modeling techniques to estimate post-fire changes in hydrologic and sedimentary processes in Mission Creek watershed. Results estimate flood discharge associated with the 100-year storm is four times more likely after fire, and even small storms will flood areas of downtown Santa Barbara. Sediment yield from the upper watershed may increase by several orders of magnitude, depending on precipitation, increasing flood risk through channel aggradation. These estimates were used to assess various pre- and post-fire mitigation projects that reduce risk for downstream communities in Santa Barbara.

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1. EXECUTIVE SUMMARY

Wildfires pose a complex management problem, especially in fire-prone areas such as southern California. Flood, sedimentation, and debris flow hazards increase in the years following fire when precipitation falls on bare hillslopes and unprotected, sometimes hydrophobic soils. Communities downstream of burned areas are at higher risk when storm runoff and erosion are intensified.

Mission Creek watershed, a small coastal watershed in southern California, has high wildfire potential indicated by regional fire history and current fuel accumulation. Mission Creek begins in steep, chaparral-covered mountain slopes and flows to the Pacific Ocean after winding through flood-prone downtown Santa Barbara. Fire in the upper watershed would greatly increase water and sediment supplies to the channel, increasing flood risk to downstream urban areas.

This project uses spatially and temporally explicit data and watershed modeling programs to quantify increases in runoff, sedimentation, and risk of debris flows in Mission Creek watershed following a potential wildfire. Current observations of post-fire hydrologic and sedimentary response in the nearby Gap Fire burn area contributed to the analysis. Fine-scale analysis allows for early planning and pre-emptive mitigation, which can supplement the typical post-fire response planned in emergency circumstances.

Approach

Three modeling programs were used to calculate post-fire changes in hydrology, erosion, and debris flow risk:

1. The ***Hydrologic Modeling System*** (HEC-HMS, U.S Army Corps of Engineers) was used to estimate post-fire storm runoff to Mission Creek.
2. The ***Erosion Risk Management Tool*** (ERMiT, U.S. Forest Service) was used to predict post-fire sediment delivery rates from surface erosion.
3. The ***Shallow Landslide Stability Model*** (SHALSTAB, UC Berkeley) was used to identify areas of the watershed where sediment supply from landsliding could increase, enhancing the risk of debris flows.

Increased flood risk from sediment accumulation in lower Mission Creek was analyzed by combining estimates of post-fire sediment delivery (from ERMiT) and discharge predictions (from HEC-HMS) with calculated sediment transport capacities for the creek.

Scenarios

Small and large fire scenarios were developed, simulating a fire in 25 and 50 percent of the upper watershed. Precipitation scenarios were developed for rainstorms with 2-5-, 10-, 25-, 50-, and 100-year recurrence intervals to represent a range of storm sizes. The effect of dry and wet antecedent soil moisture conditions on runoff was also examined.

Results

- Flooding is predicted to occur in some portion of the lower Mission Creek watershed in all fire and storm scenarios considered.
- Discharge equal to the 100-year flood, as predicted by FEMA, is four to twenty times more likely after a fire.
- Erosion rates increase by up to 385 percent for a 2-year storm and three orders of magnitude for a 100-year storm.
- Areas of chronically unstable soils increase by 53 percent in the upper and middle watershed after a large fire.
- 1 foot of sediment accumulation in lower Mission Creek decreases discharge capacity by approximately 10 percent.

Recommendations

Prioritizing post-fire risk mitigation actions improves emergency response plans and allows for pre-emptive mitigation to supplement emergency post-fire response. Recommendations focus on both specific actions to reduce runoff and sediment delivery and on coordinated emergency and long-range planning.

Emergency Post-Fire Actions:

1. *Clear sediment basins:* Clear the two sediment basins in the upper watershed to full capacity after a fire to reduce delivery of sediment to lower Mission Creek.
2. *Increase channel capacity:* Clear the creek channel of debris and vegetation to increase flow velocity and prevent blockage from large debris.
3. *Stabilize hillslopes:* Apply hydromulch to areas of upper Mission Creek watershed to reduce sediment delivery by up to 90%.

Immediate Actions:

1. *Incorporate post-fire risk into Long Range Development Plans:* Create LRDPs through the cooperative efforts of both local agencies and community organizations, with special attention given to the unique hazards created by post-fire storm management.
2. *Incorporate post-fire risk into Winter Storm Emergency Response Plan:* Incorporate post-fire flooding and sedimentation risks into management plans that detail emergency response actions during storm events.
3. *Improve information systems:* Improve public services by providing easily accessible and centralized information to citizens.
4. *Increase channel capacity:* Improve infrastructure in downtown Santa Barbara to increase capacity in the lower channel and decrease risk of flooding.

2. INTRODUCTION

Flooding and debris flows in urban areas damage property and endanger human lives. Wildfires increase the magnitude of runoff and erosion, creating a risk to downstream communities that lasts for 1-3 years after a fire (DeBano 2000, Loaiciga 2001). As development in southern California encroaches upon wildland areas, the threat of fire and post-fire impacts to lives and property continues to increase. Post-wildfire debris flows killed 16 people and caused tens of millions of dollars of property damage in Southern California in 2003 (Cannon *et al.* 2007). To aid in the management of these risks, it is imperative to understand the controlling factors behind post-fire changes in hydrologic and sedimentary processes, as well as the magnitude of change. Predictions of runoff and sedimentation after fires are important both for long-term planning of risks to infrastructure and for short-term emergency planning for public safety and hazard mitigation. It is standard procedure for local and federal agencies to conduct rapid assessments of potential hydrologic and sedimentary changes in response to a wildfire. However, making advance predictions of these phenomena in high-risk areas aids disaster planning and mitigation, flood control infrastructure upgrades (which can require decades to complete), and public awareness of possible environmental hazards.

Mission Creek watershed has a high wildfire potential based on regional fire history and fuel accumulation since the last major fire in 1964. Mission Creek floods overbank in the low-gradient reaches sporadically, with recurrence periods ranging from two to forty years, but the risks of floods and debris flows increase significantly after fire in the upper watershed (FEMA 2005a). Since the magnitude of increase in risk depends on local factors and watershed characteristics, studies of recently burned analogous watersheds can be used to inform estimations of local post-fire erosion and flooding risk.

The July 2008 Gap Fire burned approximately 9,500 acres of vegetation on steep hillslopes above Goleta, California, nine miles west of the Mission Creek watershed. Areas of the Los Padres National Forest and private lands were affected by the fire (BAER, 2008). The Burnt Area Emergency Response (BAER) Team responded by conducting a rapid assessment of the burn area and suggesting management actions to mitigate risks to the City of Goleta. As many of the burned watersheds empty through the city to the subjacent Goleta Slough near the Santa Barbara Airport, city and county implemented mitigation programs to deal with the increased sedimentation and flood risk in winter of 2008-9. The City removed debris from the channel and sediment basins, constructed racks to catch debris, and treated the land surface of burnt areas to reduce potential hazards. Early estimation of the magnitude and spatial extent of post-fire effects can improve the efficiency and timing of management decisions. These predictions can be aided by watershed analysis, field observations, and calculations of the hydrologic and sedimentary changes in the basins.

San Pedro Creek watershed was 63 percent burned in the Gap Fire and is comparable in topography, geology, hydrology and climate. These similarities provide an opportunity to refine predictions of post-fire response in Mission Creek watershed by observing the response of San Pedro watershed to the Gap Fire. Investigation of runoff and sedimentation in San Pedro Creek during the winter of 2009 supports predictions of the increases in these processes after a fire for similar watersheds such as Mission Creek watershed. This process validates predictions and provides the City of Santa Barbara and stakeholders in Mission Creek watershed with an early estimate of potential flood and sedimentation risk after a future wildfire.

2.1 Project Significance

Wildfire increases the risk of debris flows and floods in the following rainy season, threatening life and property. The upper slopes of Mission Creek watershed last burned in the Coyote Fire of 1964, after which flooding and debris flow events were recorded (FEMA 2005a). Forty-five years of vegetation recovery and fuel accumulation have increased the likelihood of wildfire in the basin.

Conceptualizing and quantifying the post-fire consequences of such a burn provides the foundation for risk analysis and mitigation planning. First, this project utilizes historical and current data about Mission Creek and San Pedro Creek watersheds to predict the potential increase in hydrologic and sedimentation processes in Mission Creek. The analysis uses field observations and hydrologic and sedimentation modeling programs to accomplish this goal. Second, the project investigates and quantifies increased risk created by these processes while integrating predictions into post-fire management and hazard mitigation plans.

2.2 Research Questions

1. How would a fire in upper Mission Creek watershed affect hydrologic and sedimentation processes in the succeeding rainy seasons?
2. What risks must be addressed to prepare downstream communities and what are the magnitudes of those risks?
3. How can early predictions of potential post-fire flood and sedimentation risk inform mitigation strategies?

2.3 Research Objectives

1. Identify the physical changes to the sedimentation and hydrologic properties of San Pedro and Mission watersheds after a fire.
2. Calculate the response of Mission Creek watershed to wildfire based on the characteristics of the watershed, and taking advantage of observations of the responses of San Pedro watershed to the 2008 Gap wildfire.
3. Assess and communicate risks to downstream communities as well as policy and management implications of the analysis.

3. BACKGROUND

3.1 Regional California Climate

Southern California has a Mediterranean climate, characterized by winter precipitation from October to May and summer drought (Goldstein *et al*. 2000). Annual average rainfall varies strongly with elevation, and between years, with some years receiving over twice the average rainfall while other years experience winter drought (Figure 3-A). This interannual precipitation variation has a significant impact on the hydrology of the region (Inman and Jenkins 1999).

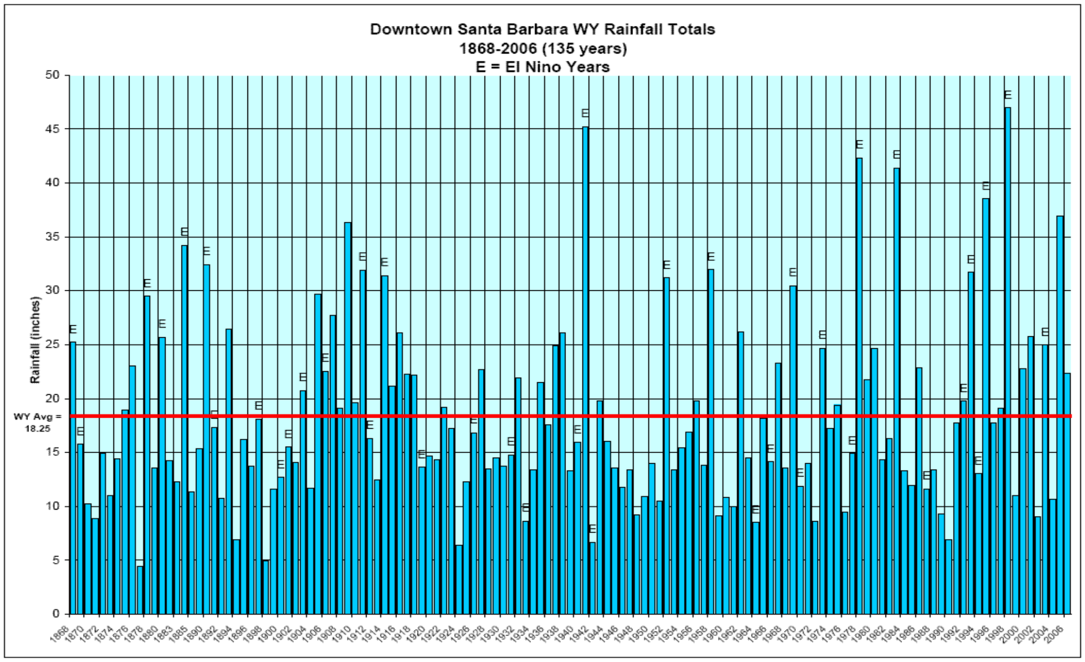


Figure 3-A: Downtown SB Rainfall Totals Compared with Average (red line).
(Santa Barbara County Water Resources Division, 2002)

There is also high precipitation variability within any given year. Variability in precipitation increases in El Niño years. Often, southern California will receive the majority of annual winter precipitation from one or two storm events. These events vary widely in duration and intensity, as well as the time interval between occurrences (Lavee *et al.* 1997). Time intervals between storm events determine antecedent moisture in soils and vegetation, which in turn, alters hydrology, erosion rates and fire regimes.

Additionally, from late fall into winter, dry, hot Santa Ana winds from eastern California are common (Callaway and Davis 1992). Santa Ana winds occur between September and April, with a peak occurrence in December. The winds are driven by the co-occurrence of a high pressure system onshore and a low pressure system off the coast. The pressure differential leads to strong winds (30 knots or 35 miles per hour or more) pushing down the coastal ranges to the sea (Raphael 2003). This phenomenon can impact the size and intensity of fires in the region.

Scientific consensus is that local Southern California climate will be altered by global climate change, but the magnitudes of change are not well defined. Most predictions are for a longer-duration fire season and rainfall events of lower frequency, but higher duration (Miller *et al.* 2003; Inman and Jenkins 1999).

3.2 Fire Regime

In Southern California, thousands of fires burn through massive tracts of wildland every year (Haston and Michaelsen 1994). The coast of south and central California is dominated by dense chaparral scrublands, one of the most fire-susceptible ecosystems in the world. Winds, as well as soil and vegetation moisture content, are important factors in the ignition of chaparral wildland fires (Zhou, Weise and Mahalingam 2005). Lightning is the only natural source of wildfire ignition, yet the most common ignition sources today are anthropogenic (Keeley *et al.* 2003). Chaparral fires tend to be active crown fires: rapidly moving fires that jump from canopy to canopy, burning through the vegetative column to the ground surface and often scorching the soil. Historic fire frequency and intensity regimes remain a topic for academic debate. Many scholars provide a fire recurrence interval of 20 to 40 years (Keeley and Davis 2006; Conard and Weise 1998). Mensing *et al.* (1999) used a 560 year record of charcoal deposits in the Santa Barbara basin to determine that the fire regime has not changed dramatically since the 1400s.

There is clear consensus that wildfires have always played a role in chaparral ecosystems, with many plant species requiring fire for seed dispersal and re-growth (Keeley 2001). It is only the risk to humans in these chaparral-covered watersheds that poses a significant "environmental" problem. As such, this paper will not examine the ecosystem impacts of fire, flooding or erosion processes. Rather, it will focus solely on the threat these processes have to human life and property.

"The general public refuses to accept that catastrophic wildfires are inevitable and that where shrublands meet human development, disaster is a likely result." (Zedler 1995)

3.3 Effects of Fire on Hydrology and Sedimentation

Wildfire Effects on Hydrology

Fires increase the runoff potential of a watershed by reducing vegetation cover and root structures and lowering the infiltration capacity of the soils. These hydrologic effects of wildfire are well-documented and increase both overall streamflow volumes and the peak flows (Meixner and Wohlgemuth 2003). Post-fire hydrograph responses are more flashy than normal runoff with more frequent flood events, especially in the first year following a fire. Annual runoff yield can be increased as much as 30% in the first year after a fire (Lavabre 1993).

The processes by which wildfires alter runoff mechanisms fall into two categories. First, removing vegetation decreases evapotranspiration of water that has infiltrated the soil, making more water available for runoff (Lavabre 1993). The result is increased streamflow volumes in the weeks and months after rainfall. Second, fire lowers infiltration capacity of soils to varying degrees by exposing bare soil to raindrop impacts that compact and seal the surface and by creating a hydrophobic layer that prevents water from entering the soil or penetrating more than several centimeters below the surface (Robichaud 2000). Particularly hot fires can alter soil chemistry, creating a layer virtually impenetrable by water (DeBano 2000). The hydrophobic layer usually occurs at depths between 2 – 8 inches (5-20 cm) (DeBano 2000, Onda *et al.* 2008, Gabet and Dunne 2003), and is maximized when fire temperatures reach 175° - 200° C (DeBano 2000).

During a post-fire rainfall event, moisture moves through the soil until it encounters the hydrophobic layer, at which point infiltration capacity drops significantly and overland flow increases. This overland flow rapidly drains to the channel network and contributes to flashy hydrograph responses with a short lag to peak (Onda *et al.* 2008). The hydrophobic layer also decreases the water-holding capacity of soils by up to 20 times its pre-fire volume (DeBano 2000, Wells 1981), increasing the quantity of water in drainage networks and contributing to increased flood peaks seen after post-fire rainstorms.

Wildfire Effects on Erosion and Sedimentation

Fire accelerates erosion and sedimentation processes, particularly in areas with steep slopes and easily eroded soils, such as those found in coastal California (Wells 1981). After wildfires, bare hillslopes have little protection from precipitation, which increases erosion from rainsplash and overland flow (Wohlgemuth 2002). Rills or small channels may form on scorched slopes as water accumulates on the hydrophobic layer, saturating soils and decreasing friction between soil particles. This creates a risk of thin debris flows which continues until the hydrophobic layer has been weathered or eroded and infiltration increases (Gabet and Dunne 2003). Debris flows are rapidly moving mixtures of mud and water that can also be initiated by the collapse of saturated soils. Larger debris flows can gather momentum and be particularly destructive when they exceed the capacity of existing channels (Wells 1981).

Rainsplash, rill erosion, slope collapse, and erosion from overland flow increase sediment yields, which may be up to 35 times higher than average during the first year after a fire (Wells 1981). Studies conducted in the San Dimas experimental forest in Southern California indicate a 2-3-fold increase in sediment production in chaparral and 7-fold increase in grassland the year after a fire occurs (Wohlgemuth 2002). Published estimates of sediment production after fires in chaparral ecosystems range between 12 and 88 tons/ acre (Keller 1997, Tyrell 1981) compared with a baseline rate of 3.9 tons/ acre (Rowe *et al.* 1949). (See Appendix 10.2.4)

3.4 Study Area

A small coastal watershed of 11.5 mi^2 (30 km^2), Mission Creek watershed runs from the undeveloped mountainous terrain of Los Padres National Forest in the Santa Ynez Mountains through residential Mission Canyon to the city center of Santa Barbara (Figure 3-B). The Mission Creek watershed was chosen for this study for its importance to stakeholders, the availability of data, and its position as a highly visible watershed likely to burn in the next decade. The topography of the watershed, a result of active tectonics, consists of a basin that rises from sea level to nearly 3,900 feet (1,200 meters) (Gurrola 2006). Thin soils and large areas of bedrock outcrop, with a dense cover of chaparral vegetation characterize the steep, upper portion of the watershed (Bean 2007). Low- to mid- density urbanization begins in the middle portion of the watershed, which is moderately steep (Vogelmann 2001). Historically, fires and debris flows have occurred in the upper and middle watershed areas (Ed Keller, pers. comm.). Lower Mission Creek passes near the historic Santa Barbara Mission and continues through the heart of downtown Santa Barbara to the Pacific Ocean. This urban area has experienced some flooding in twelve of the past 100 years (FEMA 2005b).

Nearby San Pedro watershed (Figure 3-B), studied for comparison and as an example of a burned watershed, is 7.1 mi^2 (18.5 km^2), rises 2,900 feet (880 meters) above sea level and has similar pre-fire vegetation, hydrology and geology to Mission Creek. San Pedro differs from Mission in size and land use, as the mid-watershed area is agricultural, rather than residential, and in that it empties into Goleta Slough before entering the Pacific Ocean (Vogelmann 2001). The Gap Fire of July 2008 burned 63 percent of the San Pedro watershed, with the burned area located in the upper and middle watershed (BAER 2008). This burn is similar to a scenario that could occur in upper Mission Creek watershed (David Neels, pers. comm.). Additionally, San Pedro is a useful study area because of concurrent research by USGS and the installation of a stream gauge in the lower reach.

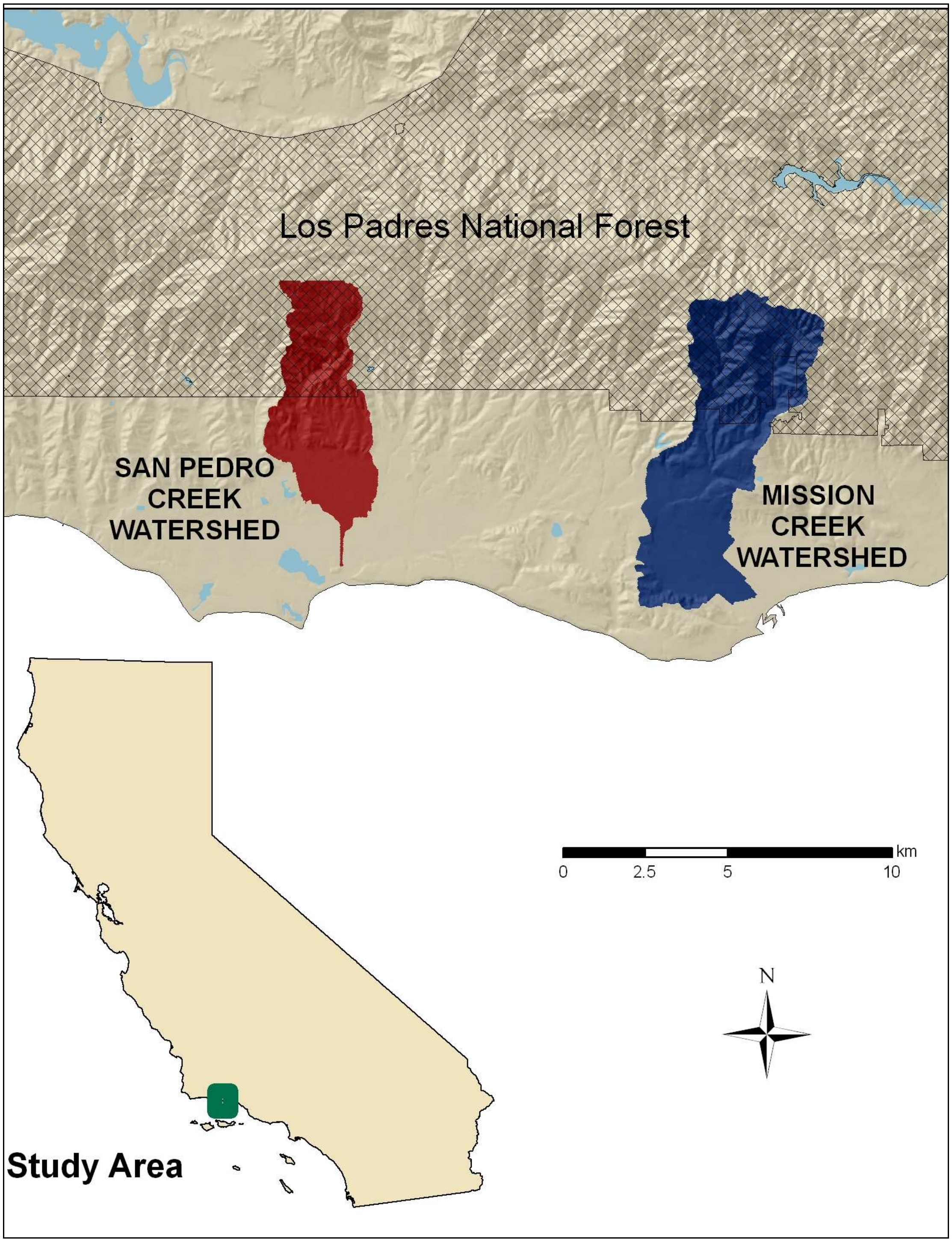


Figure 3-B: Location and extent of study area, including the Mission Creek and San Pedro watersheds. (Source Data: County of Santa Barbara, USGS, ESRI Data and Maps)

Geology and Soils

Watershed geology can determine the types of erosion to expect after a fire. The Santa Ynez Mountains, part of the rapidly uplifting Transverse Ranges (Gurrola 2006), consist of sandstone and shale (indurated clay and silt). The sandstone is more resistant than the shale and forms east-west trending ridges with shale units forming depressions and less steep portions of hillside. Both watersheds contain seven geologic units which are, from oldest to youngest: weak Juncal (shale) Formation, hard Matilija Sandstone, weak Cozy Dell Shale, hard Coldwater Sandstone, weak Sespe Formation, very weak Rincon Shale, and weakly consolidated Quaternary deposits from landslides, debris flows and the streams (Dibblee 1986). As both watersheds exhibit extensive bedrock outcroppings in areas of low rock strength, the rate of bedrock weathering to loose debris is high. The upper basins of the Santa Ynez range have considerable areas of exposed bedrock, especially on their steeper slopes. The proportion of bare rock in these watersheds has not been mapped, but using digital image processing, the area of bedrock outcropping was estimated to be between 2 percent and 9 percent in each of the upper sub-basins of the Mission Creek watershed. Mission Creek watershed has higher proportions of weaker rocks and greater volumes of runoff from the higher terrain, making it likely that rates of sediment production and erosion will be higher there than in San Pedro Creek watershed.

Understanding watershed soil characteristics elucidates the reaction of the basin to precipitation. As shown in Figure 3-C, soils depths in both watersheds are below one foot (0.3 m) in depth at the headwaters, one to two feet (0.3-0.6 m) deep in the middle watershed and two to five feet (0.6-1.6 m) deep on the historical flood plains. With large outcroppings of bedrock and low soil depths in the upper watersheds, the average water absorption capacity of the watershed is low. The soils in upper Mission and San Pedro watersheds are classified into hydrologic soil group D, reflecting their depth, rather than their texture (Soil Survey Staff, undated). As shallow soils can only accept low volumes of infiltration before becoming saturated with water, even the sandy loam soils of the Santa Barbara area, which generally have a high infiltration capacity, hold low amounts of water in areas with very thin soils (Dunne and Leopold 1978). However, a significant but unknown fraction of rainfall enters rock fractures in the first few storms of the rainy season, as indicated by the generally low response of the streamflow to rain storms at that time of year (Beighley *et al.* 2003).

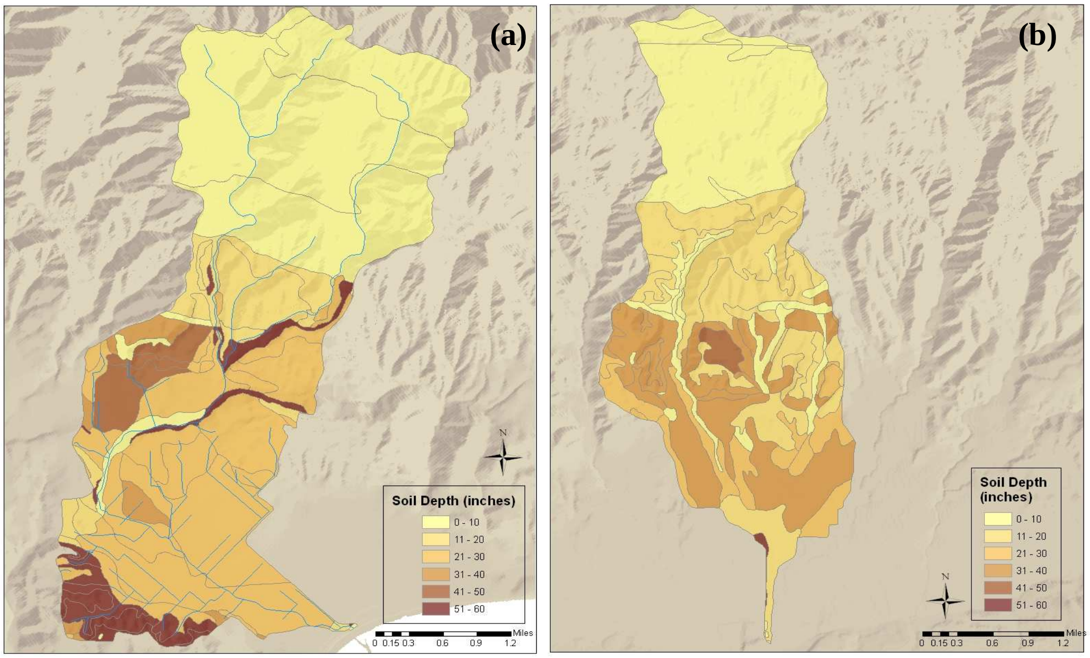


Figure 3-C: Soil Depth in Mission Creek (a) and San Pedro Watersheds (b).
(Source: Soil Survey Staff, undated)

Local Flood and Fire History

Mission Creek is typical of most streams in coastal southern California with very low stream flow throughout the year, except for a few days each year during and shortly after winter rains. With steep hillslopes and shallow soils the watershed responds rapidly to medium- and high-intensity precipitation and can create intense flooding conditions (FEMA 2005a). Such conditions can occur during events in years of high or low annual rainfall, but are more likely in high rainfall years. Total annual rainfall in downtown Santa Barbara has varied from 47 inches (119 cm) in 1998 to 4.5 inches (11.4 cm) in 1877. The steep topography of the coastal California mountain ranges causes orographic enhancement, which increases rainfall in higher elevations. Rainfall intensities of up to 2.5 inches (6.35 cm) per hour have been recorded at San Marcos Pass (elevation 2,225 feet or 678 meters) (Santa Barbara County Water Resources Division 2002). Flood records in Santa Barbara reach back more than 100 years and because of inadequate drainage in the city, flooding is relatively frequent (Table 3-A). With eight Presidential Disaster Declarations due to flooding in the past 100 years, floods are one of the most common natural disasters to affect Santa Barbara County (FEMA 2005a).

Table 3-A: History of Major Flooding Events in Santa Barbara (Source: FEMA 2005a)

Year	Dates of Floods	Notes
1861	December	Great Flood (I)
1862	January	Great Flood (II)
1914	January 15th	2-week storm
1952	January	50 homes inundated around Mission Creek
1964	November	Post-Coyote Fire flood
1969	January	Five deaths - most highways closed
1971	December	Federal disaster area declared
1978	February/March	Flooding mostly in fields and coastal areas
1980	February	Mudslides
1983	(Rainy Season)	200% normal rainfall, slope destabilization
1993	(Rainy Season)	1.25 inches in 15 minutes
1995	(Rainy Season)	510 structures flooded, all transportation cut off
1998	February	Transportation disrupted, better flood control reduced damages

Santa Barbara County also experiences frequent wildfires (Table 3-B, Figure 3-D). There have been 10 significant wild fires in the Santa Barbara area in the past 50 years. Only two, the Wheeler and Zaca fires (both mainly on U.S. Forest Service land) burned more than 100,000 acres; however, smaller fires occurring in drainages above urban areas or encroaching upon residential communities have also caused major economic damage and loss of life. Recorded fire recurrence, the time between two fires in the same geographic location, in the Santa Barbara area ranges from 6 years (between the Coyote and Cielo fires north of Santa Barbara) to 53 years (between the Refugio and Gap fires above Goleta). Upper Mission Creek watershed last burned 45 years ago in the Coyote Fire of 1964. Post-fire flooding of Mission Creek after the Coyote Fire resulted in the destruction of twelve homes and six bridges, eye witness accounts of “20-foot walls of water, mud, boulders, and trees moving down the channels at approximately 15 miles per hour,” and more than $300,000 worth of damage to public and private property (FEMA 2005a). A small portion of the Mission drainage near Rattlesnake Creek, approximately 0.2 mi^2 (0.6 km^2) also burned in the 2008 Tea Fire, though the fire was mostly contained within the Sycamore Canyon area.

Table 3-B: History of significant fires in Santa Barbara area since 1955 (Source data: CalFire, USDA Forest Service Region 5, BLM, NPS, County of Santa Barbara, USGS)

Year	Fire Name	Area Burned (acres)
1955	Refugio	79,428
1964	Coyote	65,337
1964	Polo	684
1971	Cielo	2,010
1971	Romero	14,538
1977	Sycamore Canyon	679
1979	Eagle Canyon	3,765
1979	Brad	137
1981	Rey	6,120
1990	Painted Cave	4,267
1998	Ogilvy	4,000
2007	Zaca	240,207
2007	Ranch	478
2008	Gap	9,544
2008	Tea	1,940

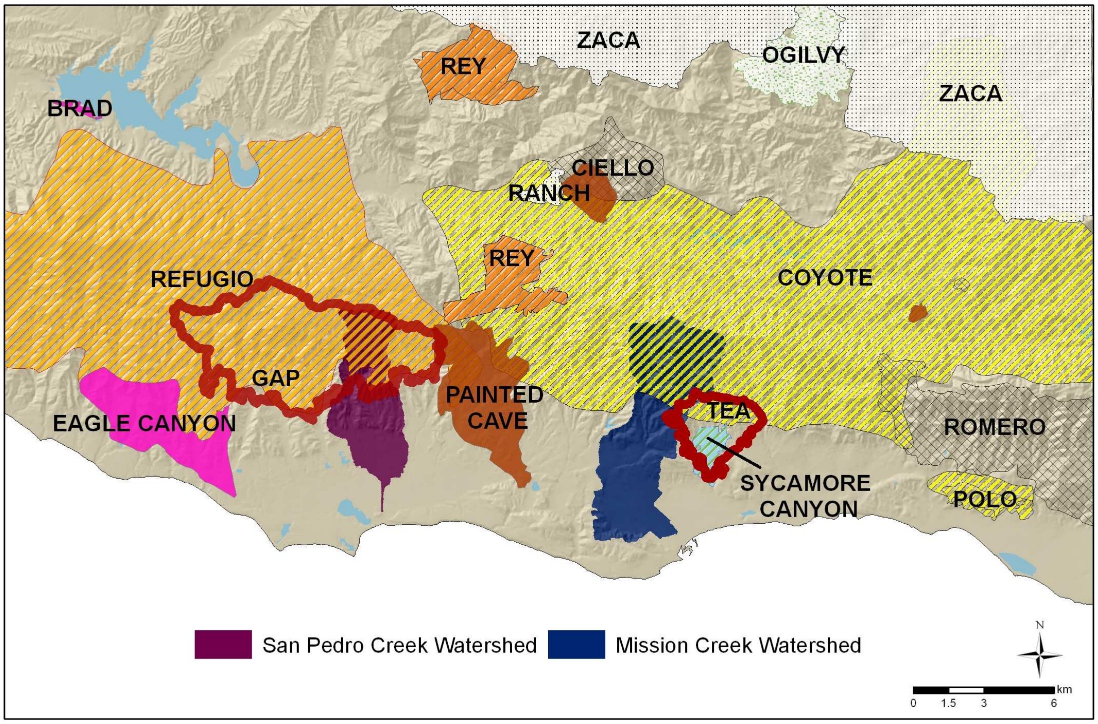


Figure 3-D: Santa Barbara fire history since 1995, with recent Gap and Tea Fires in red (Source data: CalFire, USDA Forest Service Region 5, BLM, NPS, County of Santa Barbara, USGS)

3.5 Current Post-Fire Management Policies in Santa Barbara

Most post-fire hazard policies are defined on a case-by-case basis depending on the size and intensity of the fire, primary jurisdictions affected, and funding available for mitigation activities. In Santa Barbara County, a number of state and federal agencies work with local government to ensure the reduction of risk to downstream communities from flooding and debris flows. They also seek to expand research on mitigation treatments and post-fire debris flows in order to improve future management responses. Agencies work together with the County Department of Public Works to assess which actions will diminish the risk of local flooding and damage.

Winter storms typically occur less than 6 months following the summer fire season, allowing little time for officials to enact emergency mitigation activities. Sometimes, there is hardly enough time for agencies to assess the area for potential hazards or get reactive measures approved through government pathways. For example, the Montecito Tea Fire (2008) occurred late enough in the fire season that the burned area experienced a rainstorm during the fragile period shortly after the fire was extinguished. This prompted a precautionary evacuation from neighborhoods downstream from the burn area. An effort to distribute sandbags prior to the storm did not prevent a shallow landslide from blocking a foothill roadway, initiating a coordinated emergency effort to remove debris with heavy machinery and local volunteers.

Many, but not all fires, receive federal level assessment. Fires occurring on private lands, such as the Montecito Tea Fire, do not receive this level of attention, and any post-fire strategies must be assessed and initiated by individual landowners or local agencies. In the case of the Gap Fire, since the fire was initiated in Los Padres National Forest and burned extensive tracts of land managed by the Forest Service, local officials had the support of the Burned Area Emergency Response (BAER) Team in assessing potential for post-fire flooding and sedimentation hazards. It is comprised of specialists in hydrology, soil science, biology, and engineering who predict post-fire response then recommend actions that can be taken on Forest Service property that will minimize damage human life and important resources.

Through a rapid assessment process, the BAER team developed rough estimates of increases in peak discharge and erosion rates for the burn area. The BAER team then identified more than 120 residences and 70 businesses in the drainage area below the Gap Fire that are at risk of damage from post-fire flooding and debris flows. U.S. Highway 101, railroad lines, Santa Barbara Airport, Goleta Water District water treatment plant and Cachuma Operation and Maintenance Board water pipeline were other major resources that the BAER team identified as at risk (BAER 2008).

Federal funding for emergency flood preparation in burn areas is available through the USDA Natural Resource Conservation Service (NRCS), following the creation of an Emergency Watershed Response Plan (for example, see Gap Fire Emergency Response Plan, Santa Barbara County 2008). Such plans are drafted with the best available information about local watershed conditions, fire severity and extent, and the capacity of existing flood and erosion control systems. Local officials allocate funds to mitigation measures that will ensure passage of runoff and debris through existing culverts. Actions taken by Santa Barbara County Flood Control in a post-fire response can include: hillslope hydromulching, clearing of stream channels, installation of debris racks to trap sediment and wood at strategic locations, and increase of the storage capacity of debris basins by excavation. In some cases, evacuations during large storm systems may be necessary for at least one winter following the fire.

The County and officials from the National Weather Service (NWS) are working together to create an early warning system for flash flooding in the Gap and Tea Fire areas (Boldt, NWS, 2009 pers. comm.). The NWS distributes flash flood watches then flash flood warnings based on expected total and intensity of precipitation from a certain storm, and adjusts their typical warning systems for fire affected regions. This is accomplished through a special partnership with the USGS, which uses historical events to suggest thresholds of rainfall intensities which would create high risk flooding or debris flow conditions. The rainfall intensities that trigger a flash flood watch or warning are generally about half the amount that would trigger such advisories in a non-fire region (Boldt, NWS, 2009 pers. comm.).

NWS staff also visits burn areas to discuss debris flow and flooding hazards with local Emergency, Flood, and City, and County officials. Oftentimes, the role of the NWS is to urge governments and citizens to heed weather systems, as well as to educate residents of burn areas on the NWS warning system and mitigation measures. This education is extremely important, since personal preparedness of homeowners must complement the coordinated efforts of the relevant agencies. Information provided on the County of Santa Barbara Department of Public Works website (http://www.countyofsb.org/pwd) includes homeowner manuals for preventing erosion, flood insurance links & quotes, free sandbag distribution locations, and instructions on how to create a family emergency response plan in preparation for a flood (SBCDPW, 2009).

In the case of a large storm in the winter following a wildfire, the County Office of Emergency Services (OES) coordinates logistics for multiple agencies and manages the potential for a call to evacuate certain areas at risk for flood. The Office of Emergency Services uses the NWS statements of Flash Flood Watches and Warnings to determine how to direct the activities of the Dept. of Public Works, Fire Department, Law Enforcement, Animal Control, media contacts, and other administrators. In response to heightened flood risk in the Tea Fire area, the City of

Santa Barbara OES created emergency response guidelines specific to the risk from this fire, supporting effective coordination and appropriate responses to the risk for flooding (City of Santa Barbara 2009).

Early knowledge of post-fire risk can contribute to local mitigation policies and actions. Finer-scale analysis allows for early planning and preemptive mitigation, which can supplement the normal post-fire response. Additionally, a thorough understanding of the increased magnitude of hazard following a fire can allow managers to determine an acceptable level of risk when making funding and allocation decisions.

4. APPROACH

4.1 Conceptual Approach

Risk is a product of the likelihood of occurrence and the magnitude of hazard associated with a particular event. For post-fire flooding and sedimentation, the risk of damage involves the likelihood and magnitude of the fire and the weather events following a fire. The analysis presented here assumes a portion of the upper watershed is burned, and predicts the increase in flood risk the following rainy season. Two fire scenarios and six precipitation event scenarios with varying likelihoods are examined. Post-fire increase in runoff in Mission Creek watershed is quantified, incorporating estimates of sediment that may exacerbate flooding when it accumulates in the channel and decreases channel capacity. The probability of ignition and spread of fire are not addressed.

Tools for Watershed Analysis

Three computer programs were used to calculate post-fire changes in watershed hydrologic and sedimentation properties. With each of these tools, realistic assumptions were utilized based on group knowledge, research, and observations of local conditions in the Mission Creek and San Pedro watersheds. Details of Methodology and Results, including limitations, are discussed in Section 5 (Hydrology) and Section 6 (Sedimentation).

Post-fire hydrologic watershed response was estimated using the Hydrologic Modeling System (HEC-HMS), a widely accepted rainfall-runoff prediction tool that calculates stream discharge from a precipitation event. The program was developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, and is capable of quantifying changes in runoff under different watershed characteristics, including land use, soil moisture, and most importantly for this analysis, fire.

Analysis of post-fire sedimentation included the quantification of surface erosion and spatial assessment of areas of possible debris flow production. The Erosion Risk Management Tool (ERMiT) was used to predict surface erosion by combining local climate data with soil, hillslope, and burn characteristics to estimate the probability of sediment delivery rates in the first few years after a fire. It is a web-based application developed by the U.S. Forest Service and utilized extensively by the Burnt Area Emergency Response team. The shallow landsliding stability model (SHALSTAB) was used to identify areas of the watershed where sediment is prone to mobilization by collapse events that may evolve into debris flows. This mapping program calculates the instability of a hillslope based on watershed topography and soil characteristics.

Sub-Basin Delineation

Watershed conditions vary by slope, aspect, and other topographic characteristics, therefore post-fire estimates must be made on a scale that can account for the variation in hydrologic and erosion processes. Watersheds were delineated into sub-basins using a Geographic Information System (Arc-GIS) according to a 10-meter digital elevation model and the location of stream networks obtained from U.S. Geological Survey datasets (Figure 4-A). Sub-basins were further divided into two planes separated by the stream channel. ERMiT analysis requires the definition of average basin-wide conditions at a hillslope spatial scale. The average geometry of these planes in the topographic model was utilized to create uniform "hillslopes" and calculate parameter inputs. This consistency between analyses allows for meaningful spatial comparison between runoff and sedimentation rates.

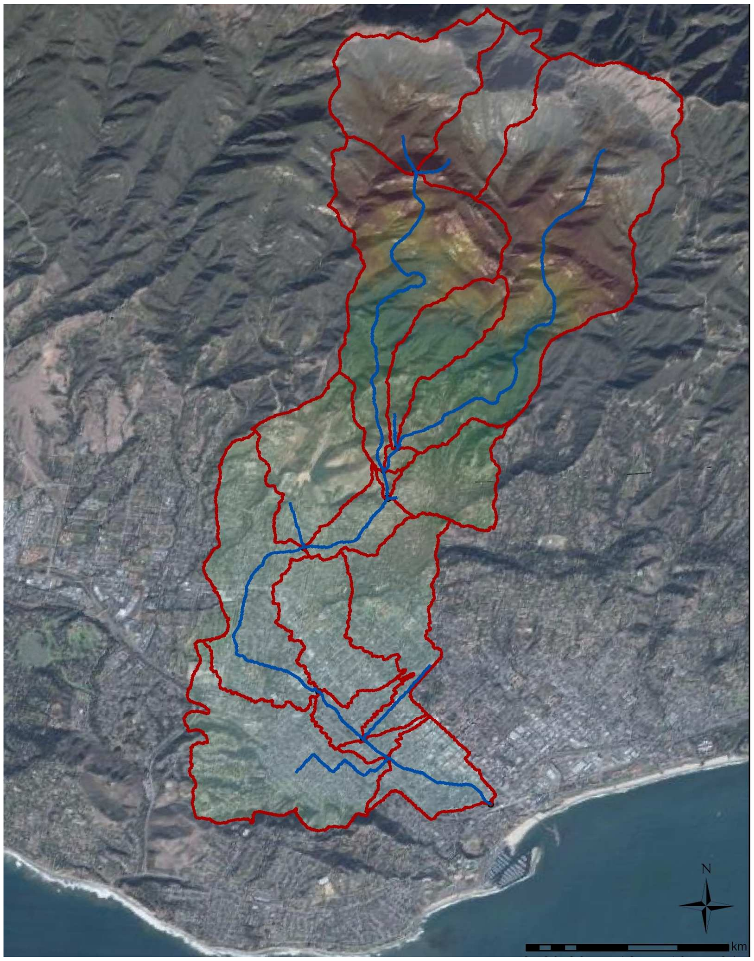
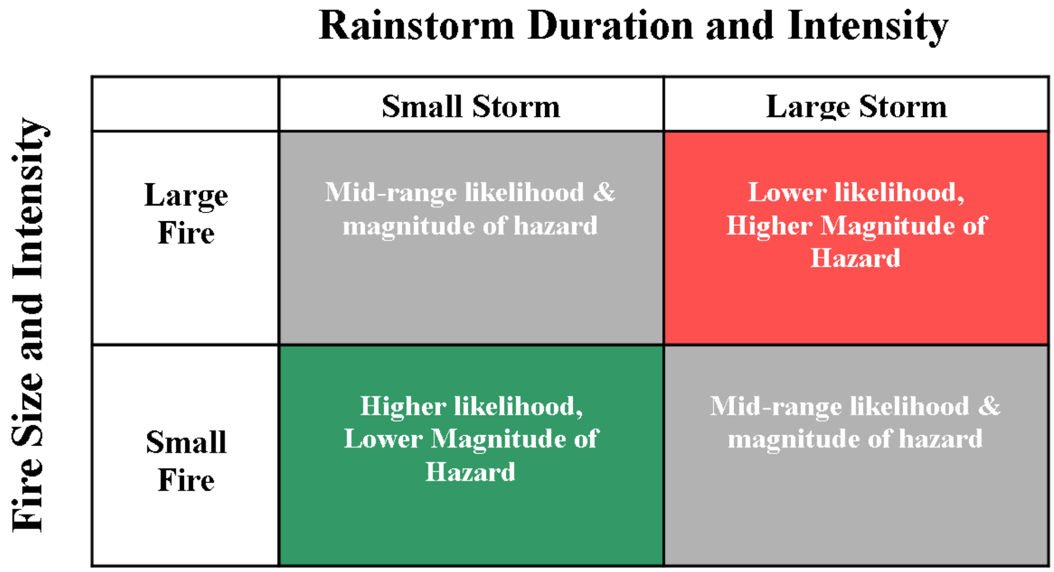


Figure 4-A: Sub-basin delineation for Mission Creek watershed used in sediment and hydrologic modeling. There are five basins in the upper watershed and twelve in the middle and lower watershed (Source Data: ESRI data and maps, DigitalGlobe 2009).

4.2 Scenario Development



	Small Storm	Large Storm
Large Fire	Mid-range likelihood & magnitude of hazard	Lower likelihood, Higher Magnitude of Hazard
Small Fire	Higher likelihood, Lower Magnitude of Hazard	Mid-range likelihood & magnitude of hazard

Figure 4-B: Risk is determined by the size and intensity of fire and precipitation.
The combinations of events that have the lowest likelihood have the highest risk and vice-versa.

Fire Scenarios

To assess risk of post-fire flooding and sedimentation, calculations were made for various combinations of realistic fire and precipitation scenarios (Figure 4-B). Small and large fire scenarios were developed based on the area of watershed burnt, with the burn always occurring in the upper Mission Creek watershed.

The large fire scenario burns the upper five sub-basins, covering 5.9 mi^2 (15.27 km^2), or 53% of the watershed. This scenario represents a fire burning down to Foothill Road, which is considered a “worst case scenario” fuel break by the Santa Barbara County Fire Department. The small fire scenario is assumed to burn only the wild areas of upper Mission Creek Watershed above the residential areas in Mission Canyon. This hypothetical fire affects three of the sub-basins of the upper watershed, covering 24% of the total watershed area (3.49 mi^2 or 7.10 km^2). The small fire scenario is considered to have a higher likelihood than the large fire, considering contemporary fire suppression techniques when lives and property are at risk.

These scenarios represent the effect of fire size on downstream flooding and sedimentation. However, as the extent of future fires is unpredictable, a fire is unlikely to burn exactly as they are delineated here. These fire scenarios make the assumption that similarly sized fires in the upper watershed will have comparable effects downstream, regardless of variations in fire boundaries.

Precipitation Scenarios

A variety of precipitation seasons or events could follow either fire scenario described above. Rainy seasons in the region are typically dominated by several large storms that provide most of the years' precipitation, so an event-driven analysis is the most appropriate for Mission Creek watershed. This project models several design storms of various recurrence intervals to mimic storms possibly occurring within a rainy season. Storms with recurrence intervals of 2, 5, 10, 25, 50, and 100 years (probability of occurring in one year is 0.5, 0.2, 0.1, 0.04, 0.02 and 0.01, respectively) were chosen to represent the range of probabilities and magnitudes of events that could occur.

5. METHODOLOGY & RESULTS: HYDROLOGY

Model Development

This project employed the Hydrologic Engineering Center's (U.S. Army Corps of Engineers) Hydrologic Modeling System (HEC-HMS) to model hydrologic response in Mission Creek watershed. The program uses a number of equations to calculate runoff volume, timing of discharge, channel flow, and routing. For each of these processes, different modeling methods can be chosen to best capture the project goals. It was decided that the SCS Curve Number method (SCS 1986, 1993) for runoff volume and the Kinematic Wave method (USACE 1979) for runoff timing and routing were most appropriate for small, steep, partially urbanized watersheds such as Mission Creek.

It was the intention of the project to use observations of the change in hydrologic response of San Pedro watershed to the Gap Fire and to apply this to expected post-fire hydrology in Mission Creek watershed. A HEC-HMS model was fully developed for San Pedro Creek watershed for this purpose. As stream gauge data were not available for San Pedro Creek prior to October 2008, San Jose Creek was used to test the reliability of parameter inputs to the San Pedro Creek model. San Jose Creek watershed is located directly to the East of San Pedro Creek watershed and has recorded 15-minute interval stream gauge data since October 2003.

Unfortunately, none of the storms in the rainy season following the Gap Fire (prior to the publishing of this paper) produced sufficient runoff for refining the model's post-fire predictions. Therefore, the HEC-HMS model for San Pedro Creek watershed was not utilized in the analysis, and the project instead used data from published literature to inform model adjustments and predict post-fire runoff in Mission Creek. If a significant storm occurs later this year, it is the intention of the authors to further substantiate model predictions by observing post-fire runoff rates in the Gap Fire area.

HEC-HMS estimates stream discharge by converting precipitation on the land surface into runoff in the stream. The program makes separate calculations of runoff for each sub-basin in the watershed, then routes water from the sub-basins into the channel. Sub-basins used for the project are described in Chapter 4 and shown in Figure 4-A. Model parameters for each sub-basin and stream reach were estimated using ArcGIS and spatial information on landcover, soil characteristics, channel geometry, and hydrography.

The SCS Curve Number Method calculates the amount of runoff from precipitation by using a parameter called the curve number. This parameter reflects the hydrologic properties of a sub-basin based on the water storage capacity of the land surface. Higher curve numbers represent lower storage and higher runoff potential. Curve number estimates for current conditions were derived using published data on land use type and hydrologic soil properties (Dunne and Leopold 1978). Curve numbers were adjusted upward to simulate the effects loss of vegetation and soil hydrophobicity after a fire. Magnitude of these adjustments was estimated from published studies of hydrologic models of local watersheds after a fire (Constantine *et al* 2008). These values were spatially averaged to obtain a curve numbers representative of the hydrologic properties of each sub-basin. A more detailed description of parameter estimation and tables of calibrated and projected pre- and post-fire curve numbers are given in Appendix 10.1.

HEC-HMS Calibration

HEC-HMS was then used to predict runoff rates for past storm events, and these were checked against stream discharges measured by the U.S. Geological Survey. Historical precipitation and stream discharge data from 5 rain gauges and 2 stream gauges in and near Mission Creek watershed were used (Figure 5-A). Curve number parameters were then systematically adjusted until modeled discharge mirrored recorded values, a process known as calibration. The Mission Creek watershed HEC-HMS model was calibrated for two storms in 2005, January 7-11 and February 16-23. The January storm had higher antecedent rainfall, although the typical measure of antecedent soil wetness (defined as total rainfall in the five days prior to a storm) characterized the initial soil moisture as dry (Dunne and Leopold 1978). The degree to which soils are saturated with water prior to a storm, or antecedent moisture condition, affects how much precipitation is absorbed by the soil before it begins to run off, and higher initial soil moisture results in higher runoff volumes.

Pre-fire dry antecedent moisture models were calibrated to the January 7-11, 2005 storm, approximately a 10-year recurrence event. The modeled hydrograph for this storm accurately predicted the timing of peak flows and the magnitude of these peaks within 17 percent for the two USGS gauges on Mission Creek (Figure 5-B). The model was validated using the February 16-23, 2005 storm, approximately a 1-2 year recurrence event on dry antecedent moisture, and it continued to make good predictions on the timing and magnitude of peak flows (Figure 5-C). The model was also checked against measurements for three smaller storms during 2006 (less than 1-year recurrence events). For these smaller storms, the model over-predicted runoff by roughly 100 percent, implying that accuracy for smaller storms is not as great as for 2- to 10-year recurrence events.

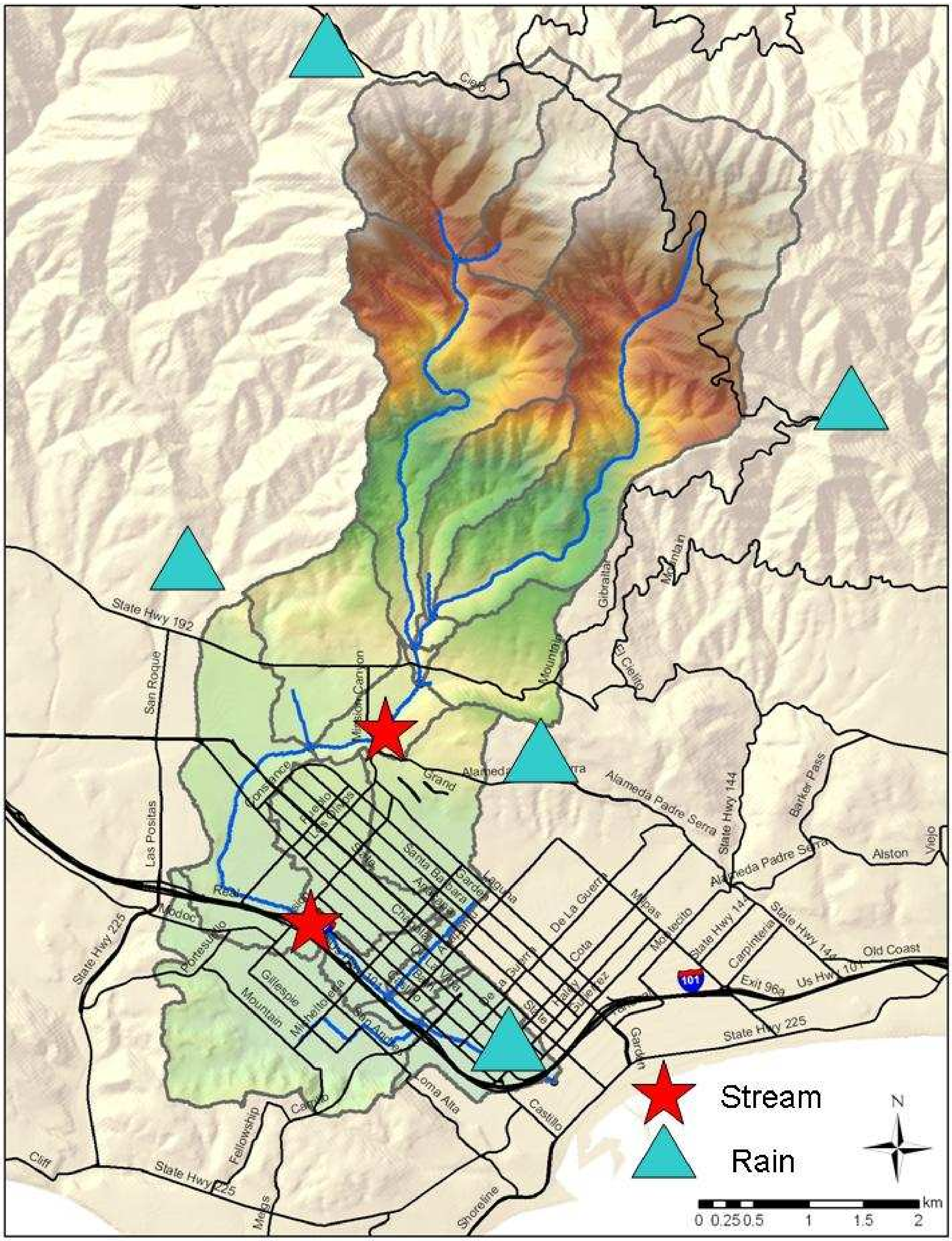


Figure 5-A Five rain gauges and two stream gauges that were used for modeling hydrology in the Mission Creek watershed (Source data: U.S. Geological Survey, ESRI Data and Maps, Santa Barbara County Flood Control)

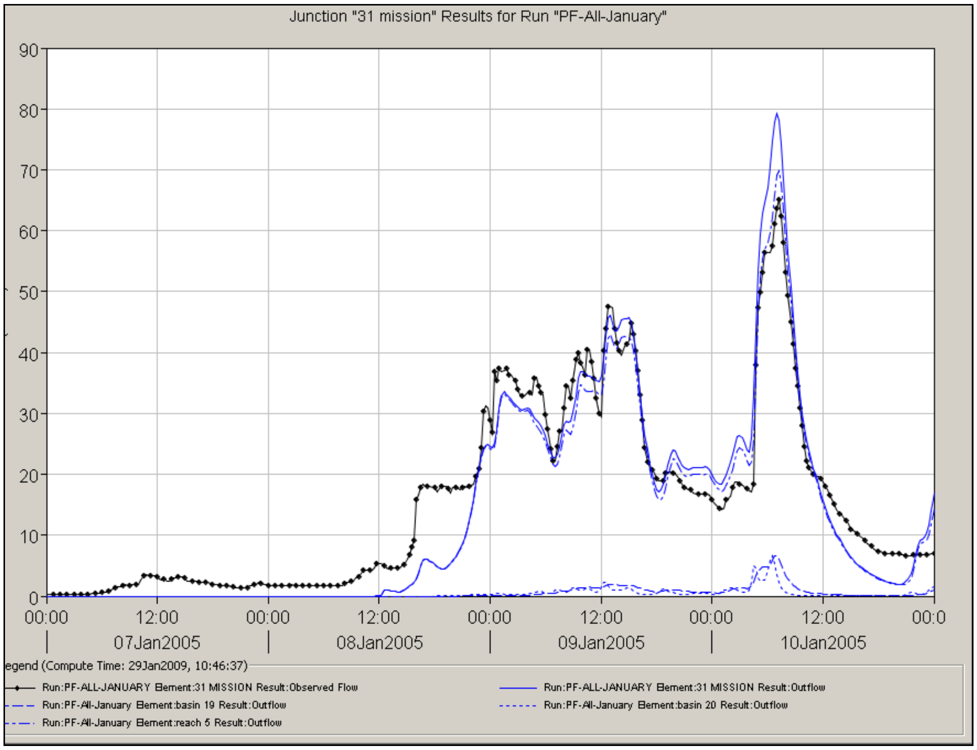


Figure 5-B: Hydrograph of Modeled (Solid Blue Line) vs. Observed Discharge (Black) for January 7-11, 2005 at the Mission Creek gauge at Mission Street (USGS 11119750).

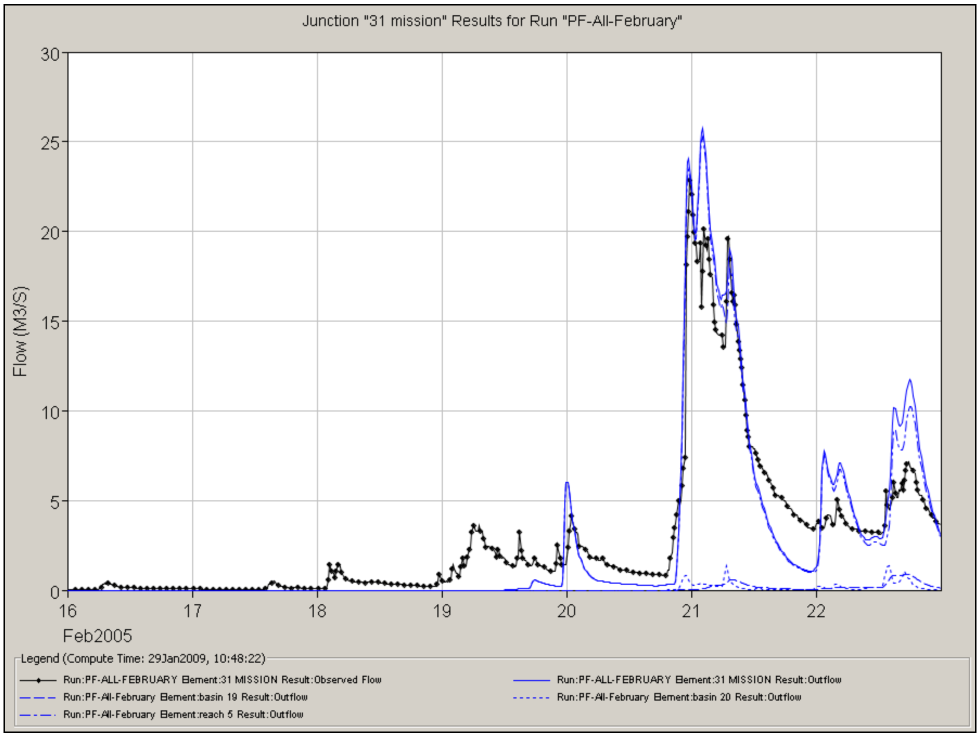


Figure 5-C: Hydrograph of Modeled (Solid Blue Line) vs. Observed Discharge (Black) for February 16-23, 2005 at the Mission Creek gauge at Mission Street (USGS 11119750).

Both the January and February storms were characterized as beginning on dry antecedent moisture, as characterized by the amount of rainfall in the five days prior to the event (Dunne and Leopold 1978). However, there was most likely higher moisture content in the deeper soil and fractured bedrock layers, so that infiltration was decreased as compared to a storm earlier in the rainy season. For example, when the calibrated model for dry antecedent moisture was used for the first storm in the 2005 Water Year, October 16-20, 2004, the simulated runoff significantly exceeded the magnitude of measured peak flows. The likely cause of this is the underlying geology of the Mission Creek watershed, which absorbs significantly more water during the first precipitation events each winter. This infiltration is significantly decreased as more rain falls on the watershed and this longer term storage is filled. In fact, the first precipitation of each year in Santa Barbara rarely creates runoff in Mission Creek, and some years with low rainfall experience minimal streamflow (Figure 5-D). As this project is primarily interested in risk from larger storms that create a significant amount of runoff, and these storms usually occur later in the winter, this HEC-HMS model is calibrated appropriately. The model is less accurate for small storms early in the winter.

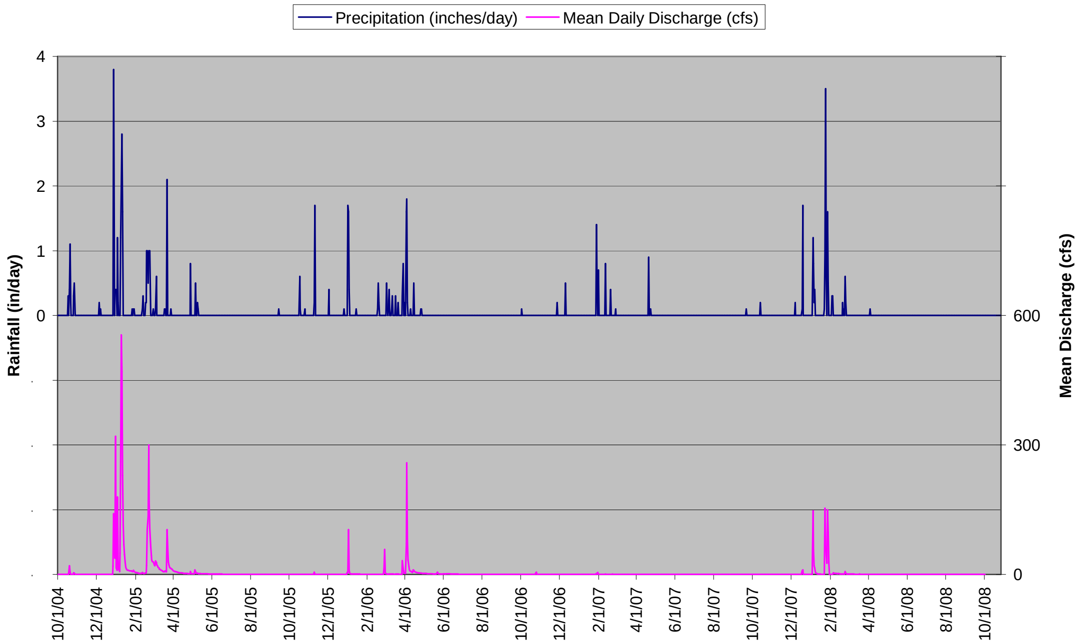


Figure 5-D: Daily Rainfall (Goleta Airport) and Discharge at Mission Creek (Rocky Nook Park USGS Gauge 11112745); Oct 2004-Sept 2008. The first rainfall event (blue line) in the cluster of storms that represents the winter rainfall, rarely produces runoff, as indicated by the pink lines directly below. Some winters produce no runoff (Oct 2006-Oct 2007).

Scenario Analysis

Storm recurrence intervals of 2-, 5-, 10-, 25-, 50-, and 100-year were derived from storm intensity tables from Santa Barbara County Flood Control. Discharge in Mission Creek for these design storms was predicted for four scenarios: (1) pre-fire on dry antecedent moisture conditions (baseline scenario), (2) small fire and dry antecedent moisture, (3) large fire and dry antecedent moisture, and (4) large fire and wet antecedent moisture. Our analysis focused on the controlling factors of post-fire peak discharges, such as fire size and antecedent moisture, and how these factors contribute to flood hazard in Mission Creek watershed. (A table of peak discharge and total discharge results is provided in Appendix 10.1.4)

24-hour design storms were created in HEC-HMS, which is the most common storm duration used in the United States for drainage system planning (USACE 2000a). Historical rainfall intensities and recurrence intervals for each rain gauge were obtained from Santa Barbara County records. For each rain gauge, we constructed a storm using the alternating block method, in which the maximum 15-minute intensity is placed in the middle of the total duration (24 hours). The rainfall durations are then placed in descending intensities on either side of the central block (USACE 2000a).

Results

HEC-HMS results showed a range of increases in peak discharge from pre-fire to post-fire conditions for given storms (Figure 5-E). Model output was consistent with expected results, as predicted discharge increases with increasing fire size, antecedent soil moisture, and storm size. The percentage increase in peak discharge is greatest for small storms when there has been a large fire and antecedent moisture is high. For example, a 5-year storm that occurs after a large fire with high antecedent moisture, will produce a discharge equal to the 100-year storm pre-fire.

The smallest increase was 55 percent for a 25-year storm, after a small fire. A large fire and wet antecedent conditions resulted in a 400 percent increase in runoff during a 2-year storm. Estimated total discharge volume increased by 22 percent (100-year recurrence interval storm, small fire) to 146 percent (2-year recurrence interval storm, large fire, wet antecedent moisture).

The effects of a small fire increase runoff peaks from 55 percent to 155 percent of baseline conditions (the increase from the green line to the yellow line in Figure 5-E). A 2-year recurrence interval storm that would create peak discharge of 848 cubic feet per second (cfs) when the watershed is unburned results in 2,155 cfs discharge in the small fire, dry antecedent moisture scenario, a similar discharge to what would be expected with a 10-year recurrence interval storm before a fire.

As would be expected, the large fire scenario had a more pronounced impact on peak discharge than the small fire scenario. For a 25-year recurrence interval storm on dry antecedent moisture conditions peak discharge increased to 55 percent of baseline conditions for the small fire scenario and 115 percent for the large fire scenario. The small fire scenario predicted discharge peaks comparable to those of the 100-year recurrence interval storm on an unburned watershed. This indicates a fourfold increase in the risk of the100-year flood when half the upper watershed is burned.

Antecedent moisture conditions also affect the amount of runoff created in the Mission Creek watershed. When compared to dry antecedent moisture with the same fire scenario, peak discharge when soils are wet increases by 24 to 28 percent. For example, a 100-year recurrence interval storm occurring on a large fire with dry antecedent conditions has a predicted peak discharge of 12,574 cfs, and the peak discharge with the same fire and storm has an estimated discharge of 14,057 cfs.

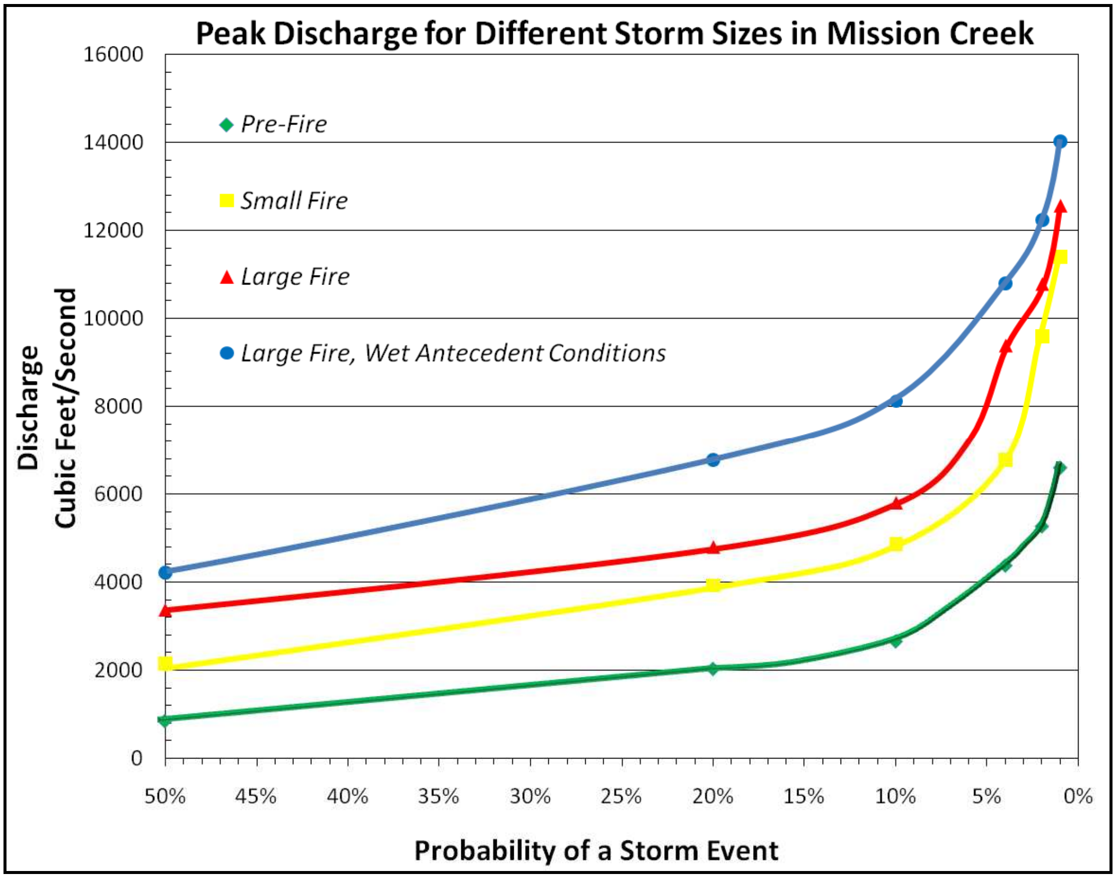


Figure 5-E: Predicted Peak Discharges at the Mission St. gauging station (USGS 11119750) for the 2-, 5-, 10-, 25-, 50-, and 100-year storms under four scenarios

HEC-HMS predictions for design storms on an unburned Mission Creek watershed are consistent with predictions made by FEMA and a log-Pearson Type III analysis. FEMA estimates a 100-year flood at 7,050 cfs in Mission Creek (FEMA 2005a), comparable to the model's estimate of a 100-year discharge of 6,600 cfs. A log-Pearson type III analysis, a widely accepted method for doing flood frequency analysis in the United States, was also conducted using USGS gauge *11119750* on Mission Creek. Log-Pearson type III is a theoretical probability distribution that is used to estimate peak discharges of different recurrence intervals from the historical record of annual maximum peak discharges (Bedient and Huber 1992). From the historical record of 38 years, peak discharges with recurrence intervals of 2-, 5-, 10-, 25-, 50- and 100-years were calculated. The HEC-HMS model estimates compare favorably to the results of the log-Pearson type III analysis. The log-Pearson analysis predicted a 100-year discharge of 6,800 cfs which is comparable to the HEC-HMS model's prediction of 6,600 cfs (see Appendix 10.1.5).

Limitations of Analysis

Models of environmental processes such as hydrology and sedimentation provide valuable tools for assessing the likelihood and magnitude of the hazards analyzed in this project, but there are known limitations to their use. It is important to recognize the limitations of the analysis so that one may effectively assess and communicate predictions and results. This section provides a discussion of the limitations of each of the three programs used for flood, sedimentation, and debris-flow prediction.

The HEC-HMS model constructed for Mission Creek is best at estimating discharge for 2- to 10-year recurrence interval storms, and uncertainty increases greatly with storms outside of a the 2- to 25-year recurrence interval range. The ability of the model to accurately predict the magnitude of flood peaks for storms larger than the 10-year storm has not been validated as these storms are infrequent and stream gauge data is unreliable when storms cause Mission Creek to flow overbank.

Modeled discharge predictions also work best for rainfall events in the middle or late in the rainy season. Predictions will overestimate runoff from unburned areas when little or no precipitation has occurred in the month or two prior. This is largely attributed to the fractured rocks of the basin, which appear to absorb more water than is expected by normal parameterization of the model with hydrological properties transferred from otherwise comparable soils.

6. METHODOLOGY AND RESULTS: SEDIMENTATION

Assessment of sediment sources and potential production volumes is an important component of a post-fire risk analysis of Mission Creek. If sediment accumulates on the stream channel bed, channel capacity is diminished and the risk of overbank flooding increases. The results of two computer models contributed to our analysis of the potential increase in sediment accumulation in the creek after a fire. Each model examines a certain type of sediment erosion process: widespread water erosion of burned hillslope surfaces, and more localized landslides that evolve into debris flows. The surface erosion model also has the capacity to address certain hillslope mitigation treatments that are commonly considered in post-fire emergency situations. Calculations are verified through the use of published literature and field observations in the San Pedro watershed after the Gap Fire.

6.1 Surface Erosion Model (ERMiT)

The Erosion Risk Management Tool (ERMiT) is a web-based application designed and maintained by the United States Forest Service, Rocky Mountain Research Center. ERMiT was created as a user-friendly interface to the Water Erosion Prediction Project (WEPP) software in order to assist managers with post-fire erosion prediction and mitigation. (For a schematic diagram and description of the WEPP program, see Appendix 10.2.3)

The ERMiT interface allows the user to manipulate parameters affected by a wildfire, such as soil burn severity class, pre-fire vegetation descriptors, and soil characteristics (soil texture, rock content). The program also uses information hillslope gradient and horizontal length. Historic climate data for the specific geographic location is integrated into WEPP through software called PRISM (Appendix 10.2.5). Using PRISM to characterize storms of 2-100 year recurrence intervals, ERMiT produces an event-driven estimate of sediment delivery rates. Each ERMiT output is based on 20-40 individual WEPP model runs for each of five years following a wildfire. Sediment delivery estimates are calculated for single storm events, rather than a full winter season of different-sized storms, which complements an event-driven hydrologic analysis. Additionally, ERMiT estimates the effects of various hillslope treatments such as hydromulching, seeding, straw mulch and erosion barriers. See Appendix 10.2.1 for detailed description of parameters, inputs, and sensitivity analysis.

ERMiT makes its calculations on a hillslope scale, allowing for the estimation of sediment yield ranges from various areas in the watershed, characterized by their average hillslope gradient and length, and soil type. Figure 6-A is an example of the ERMiT Sediment Delivery Exceedance Probability graph for a sub-basin in upper San Pedro watershed. This graph predicts the minimum amount of sediment expected from a particular storm event. The x-axis indicates sediment in tons/acre delivered to the channel and available for transport downstream. The y-axis indicates the probability of a single storm event occurring. Each colored line represents a winter storm following wildfire, with red indicating the first year after a fire, and so on. The expected sediment delivery values decrease dramatically from one year to the next following a fire due to the natural buffering capacities of re-vegetation and soil recovery.

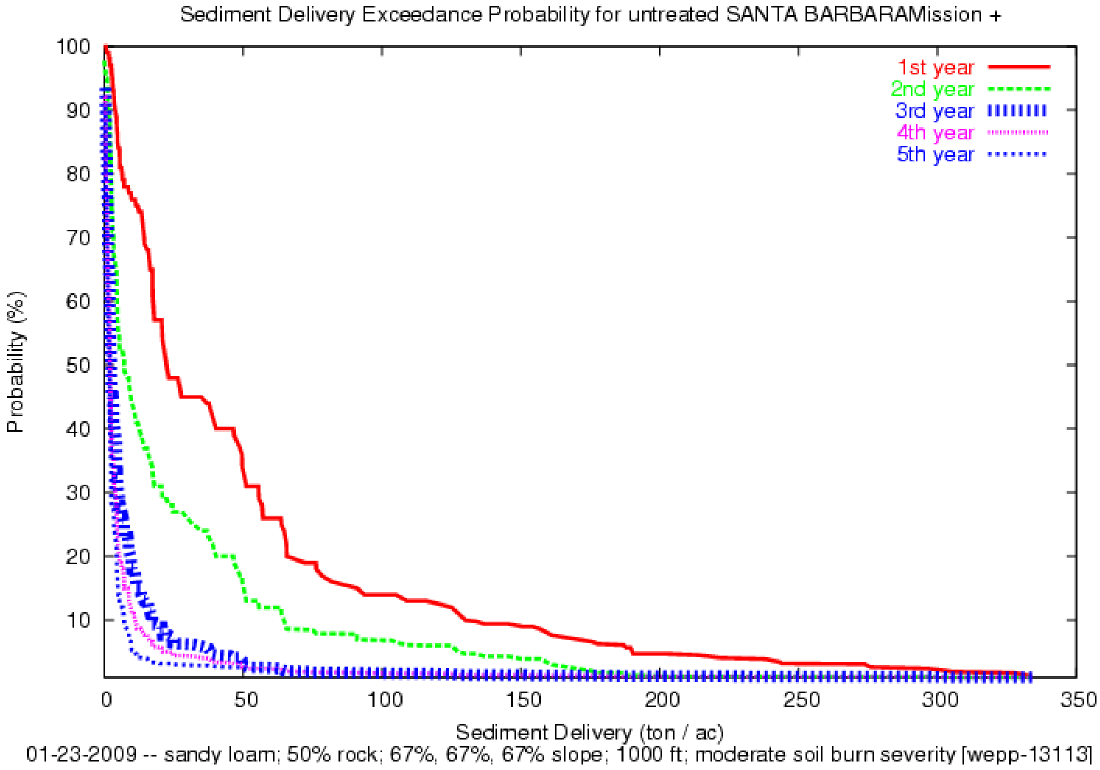


Figure 6-A: A sample output from one sub-basin in post-fire San Pedro watershed. The y-axis is the probability in percent of a particular size storm in any given year. The x-axis is the sediment delivery in tons/acre predicted for that sub-basin.

Scenario Analysis

After sub-basin delineation for both San Pedro and Mission Creek Watersheds (See Section 4.1), input parameters for each of the five upper sub-basins of Mission were calculated using Arc-GIS and observations of fire effects in San Pedro. Using ERMiT in this manner allows for the identification of hillslopes in Mission with high sediment delivery potential, and provides a range of post-fire erosion rates for the upper watershed.

Total sediment deliveries after a small and large fire in Mission were calculated by multiplying the sediment delivery rate for each sub-basin with the area of that sub-basin. In our large fire scenario, all five upper sub-basins were burned, while only three sub-basins were burned in the small fire scenario. Baseline erosion rates for the Mission Creek Watershed of 3.9 tons/acre (Rowe *et al.* 1954) were used for calculations of total sediment production in the unburned sub-basins. Total sediment delivery for the entire watershed was determined by summing results from each sub basin in a burned or unburned state, depending on the scenario.

The analysis only examines the upper watersheds for two reasons. Due to local watershed characteristics, the upper 50 percent of a watershed produces approximately 60 percent of the total runoff measured at the bottom of Mission Creek, and impacts erosion proportionally. Also, the lower portions of both watersheds have low gradients and are covered with asphalt with only small areas exposed to erosion.

Results

Combined sediment delivery rates from ERMiT (in tons/acre) for both watersheds are presented in Figure 6-B. The small fire scenario for Mission Creek watershed produced similar sediment delivery rates as estimated by the BAER Team for San Pedro watershed following the Gap Fire. For the 2-year storm event following a small fire, ERMiT predicted an average of 14 tons/acre of sediment lost in the upper watershed, or a range of 3.9 tons/acre (for unburned regions of the upper watershed) to about 23 tons/acre in areas of steep slopes. In contrast, for the large fire scenario, ERMiT calculated an approximate 30 percent increase in sediment production. A 2-year event following a large fire in Mission yields an average of 20.4 tons/acre (Range: 14-25 tons/acre).

The difference between the large and small fire scenarios widened for less likely scenarios: namely the 50- and 100-year storm events. A small fire in Mission followed by a 100-year storm will produce an average of 171 tons/acre. A large fire could produce as much as 265 tons/acre, a 55 percent increase in sediment delivery from the small fire scenario.

Total post-fire sediment production values, shown in Table 6-A, are significantly higher than predicted sediment delivery with a background rate of 3.9 tons/acre (Rowe *et al*. 1954). Total sediment production was calculated by multiplying the rate of delivery from ERMiT by the area of the watershed corrected for bedrock exposure. Results indicate that a 2-year storm after a small fire (which burns 1,818 acres) could mobilize 41,470 tons of sediment into Mission Creek. A large fire, burning 3,774 acres of the upper watershed, could produce 67,776 total tons of sediment. This is 385 percent higher than background sediment production rates for the upper watershed of 13,979 tons (Rowe *et al.* 1954). A large storm (100-year recurrence interval) following a large fire in upper Mission Creek watershed could produce an increase of 90 percent from the small fire scenario.

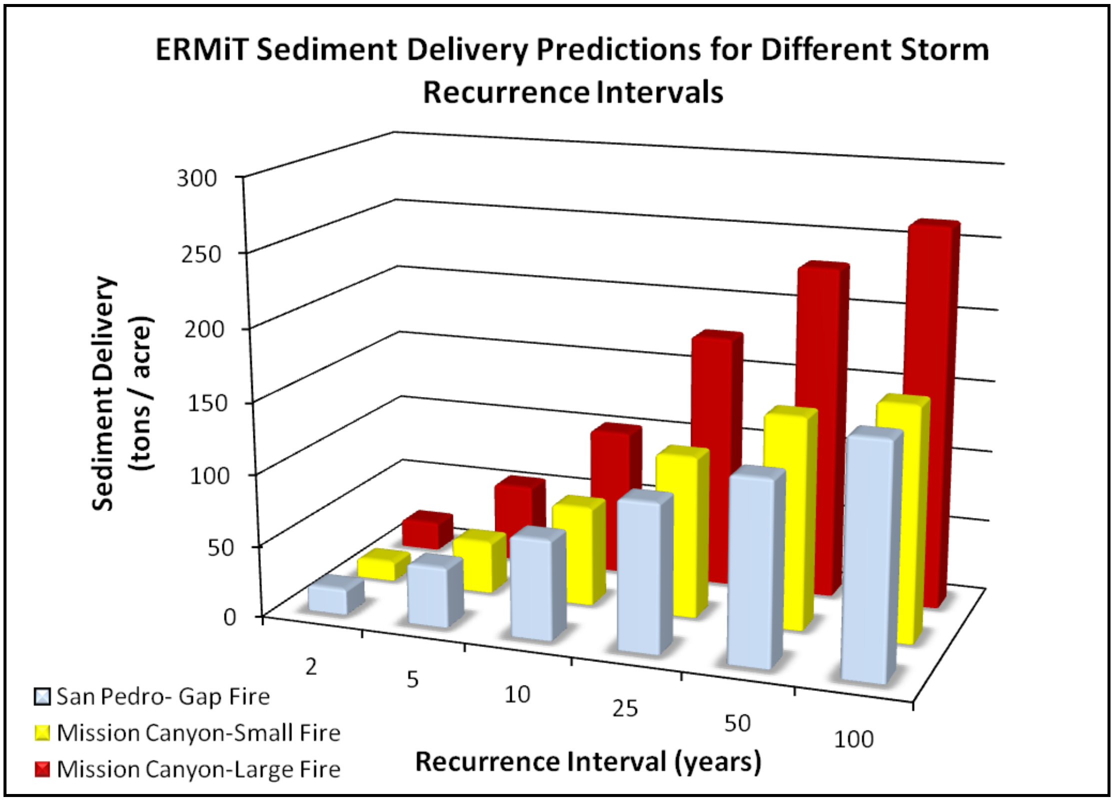


Figure 6-B: ERMiT predicted sediment delivery in tons/acre averaged over the entire watershed.

Table 6-A: Summary of Total Sediment Delivery calculated from ERMiT results for large and small fires in the Mission Creek Watershed. Total sediment delivery **for Mission has been adjusted for bedrock exposure.**

Storm Recurrence Interval	LARGE FIRE: Mission Creek Total Sediment Delivery (tons)	SMALL FIRE: Mission Creek Total Sediment Delivery (tons)
2-year	***67,776***	***41,470***
5-year	***193,387***	***105,546***
10-year	***369,420***	***197,850***
25-year	***637,960***	***337,334***
50-year	***835,911***	***440,117***
100-year	***936,100***	***483,870***

These results suggest that the risk associated with post-fire flooding is heavily dependent on the intensity of rain events the following winter and the size of the watershed area burned. Sediment delivery estimates for each fire scenario increase rapidly between small storms, and then plateau from the 50-year event onward. This suggests that there may be a certain threshold of storm event, where the maximum amount of sediment is being mobilized.

ERMiT Validation

Regular communication with US Forest Service personnel confirmed that chosen input parameters were representative and appropriate and that the predictions align well with experience in other burned watersheds (William Elliot *pers. comm.* 2008). Additionally, published field measurements of sediment delivery from post-fire watersheds were utilized to verify chosen input parameters (Appendix 10.2.4). Table 6-B lists sediment delivery in tons/acre from various historical studies in California chaparral in the year following a fire, using either field estimates or calculations from sediment basins. The measured sediment yield ranged from about 13 tons/ acre to 88 tons/acre for 2- to10-year storm events during the following winter.

Table 6-B: Post-fire sediment delivery from published literature. References: (1) Wells 1981, (2) Krammes 1960, (3) Keller 1997, (4) Tyrrel 1981.

Published Literature	Sediment Delivery (tons/acre)
CA Chaparral, Pine Canyon, CA[1]	***13***
Johnstone Fire, San Dimas, CA (2 yr rainstorms)[2]	***25***
Painted Cave Fire, Santa Barbara, CA (2-10 yr rainstorms)[3]	***33***
Panorama Fire, San Bernardino Forest (mixed treatments)[4]	***47-88***
Rowe *et al* (1954) San Pedro Creek post-fire calculation	***97***
Rowe *et al* (1954) Mission Creek post-fire calculation	***124***

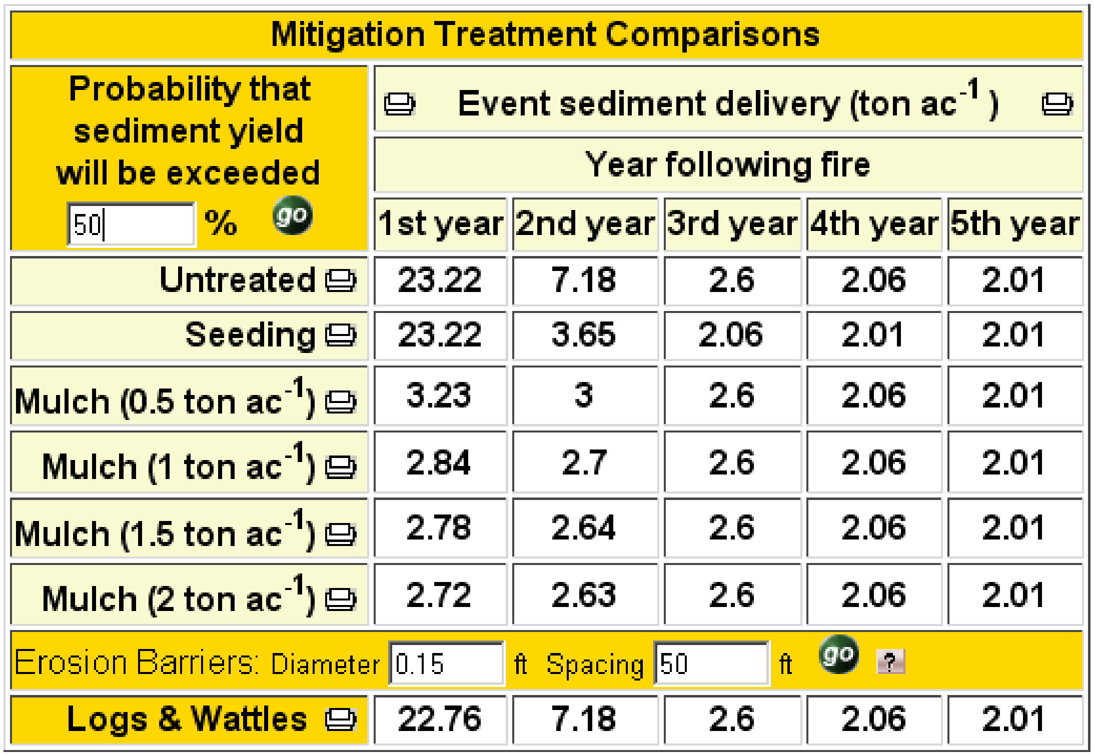
Table 6-C: Post-fire sediment delivery from ERMiT in tons/acre to be compared with the BAER team estimate of 53.6 tons/acre in the San Pedro Watershed after a 2-year recurrence interval storm.

Storm Recurrence Interval	LARGE FIRE: Mission Creek Sediment Delivery (tons/acre)	SMALL FIRE: Mission Creek Sediment Delivery (tons/acre)	GAP FIRE: San Pedro Sediment Delivery (tons/acre)
2-year	***20***	***14***	***18***
5-year	***55***	***37***	***42***
10-year	***103***	***69***	***70***

ERMiT estimates of sediment delivery from the San Pedro watershed after the Gap Fire are comparable to these published values (Tables 6-A and 6-B) Comparing San Pedro ERMiT results with the BAER Team estimates was a final valuable step in validation of the project methodology. The BAER Team estimates a 53.6 tons/acre sediment delivery for the entire San Pedro watershed during a 2-year storm event the year following the Gap Fire. Individual ERMiT sub-basin results for this size storm ranged from about 8 tons/acre to 40 tons/acre throughout the San Pedro Watershed, depending on the hillslope characteristics.

ERMiT Application to Mitigation Treatments

One of the greatest strengths of the ERMiT model is its practical nature. This simple, web-based program can be utilized by emergency response teams to perform rapid assessments based on just a few characteristics of the burned watershed. It also provides estimates of what can be expected from various mitigation measures. The mitigation treatments component of ERMiT allows managers to input the particular storm event they would like to plan for as a “probability that sediment yield will be exceeded”. The model equates this parameter to the probability that a larger storm will occur in a given year. Once a manager has decided what storm event should be used for planning, ERMiT provides tables indicating how various mitigation treatments might be utilized to decrease sedimentation. Figure 6-C is a sample set of ERMiT calculations for erosion rate decrease with various mitigation treatments, including hillslope treatments such as hydromulching, seeding, straw mulch and erosion barriers. Ultimately, ERMiT gives managers support for difficult post-fire decisions based on fundamental hydrologic and sedimentary theory.



Mitigation Treatment Comparisons

Probability that sediment yield will be exceeded 50 % go	Event sediment delivery (ton ac^{-1})				
	Year following fire				
	1st year	2nd year	3rd year	4th year	5th year
Untreated	23.22	7.18	2.6	2.06	2.01
Seeding	23.22	3.65	2.06	2.01	2.01
Mulch (0.5 ton ac^{-1})	3.23	3	2.6	2.06	2.01
Mulch (1 ton ac^{-1})	2.84	2.7	2.6	2.06	2.01
Mulch (1.5 ton ac^{-1})	2.78	2.64	2.6	2.06	2.01
Mulch (2 ton ac^{-1})	2.72	2.63	2.6	2.06	2.01
Erosion Barriers: Diameter 0.15 ft Spacing 50 ft go ?					
Logs & Wattles	22.76	7.18	2.6	2.06	2.01

Figure 6-C: Mitigation Treatment Comparison from ERMiT for a small, steep sub-basin in the upper Mission Creek Watershed. Sediment delivery in tons/acre is presented for a 50% exceedance probability, or a 2-year storm event, for the first 5 years following a fire.

Mitigation treatments are calculated in ERMiT by increasing the occurrence probability of less erodible soils in the watershed and decreasing the occurrence probability of erodible soils (Robichaud *et al.* 2007). The effectiveness of various mitigation treatments in specific burned watersheds, as well as the accuracy of ERMiT sediment delivery reduction, is a subject for further study. In general, Robichaud *et al.* 2007, have found that ERMiT “…under-predicts sediment yields from untreated and seeded hillslopes in the Colorado Front Range, but is much more accurate for predicting sediment yields from hillslopes treated with straw mulch."

Straw mulch and hydromulch are widely used after fire to decrease and slow runoff, protect bare soils from raindrop impact, and decrease erosion rates on hillslopes. Straw mulch is hand-applied to the surface and sometimes anchored to the ground with a crimping-device, but local Santa Ana and "sundowner" wind patterns create unfavorable conditions for this treatment. Therefore, hydromulch is a practical option for local burn areas because it contains a binding agent (guar gum) and can be sprayed from trucks, or aerially in areas with no road access, and is rarely affected by wind. ERMiT considers hand-applied straw mulch in its effectiveness measure, with application rates ranging from 0.5 tons /acre to 2 tons/acre. In this analysis, straw mulch treatment is used as a proxy for hydromulch treatment, as it is the most accurate estimate of mulching effectiveness available.

Table 6-D: ERMiT estimation of the decrease in sediment delivery caused by application of mulch in upper Mission Creek watershed. Mulch application is one ton/acre.

Storm Event Probability	Average Sediment Delivery *No Treatment*	Average Sediment Delivery *Mulch*	% Reduction in Sediment Delivery
2 yr recurrence	20 tons/acre	3 tons/acre	85%
5 yr recurrence	55 tons/acre	6 tons/acre	88%
10 yr recurrence	103 tons/acre	10 tons/acre	90%
25 yr recurrence	177 tons/acre	17 tons/acre	90%
50 yr recurrence	231 tons/acre	73 tons/acre	69%
100 yr recurrence	265 tons/acre	265 tons/acre	0%

ERMiT predicts straw mulch treatment of hillslopes will reduce sediment delivery rates by 85-90 percent for small to moderate size storms in Mission Creek watershed (Table 6-D). However, the effectiveness of mulch on the hillslopes declines dramatically for lower probability storms, such as the 50 and 100 year recurrence storms. Expert opinion and early observations on United States Forest Service test plots confirm this loss in effectiveness for large storms (Mary Moore, USFS, pers. comm.).

Many post-fire mitigation studies are not peer-reviewed and are generally inconclusive with highly variable results. MacDonald and Robichaud (2008) conducted a four year study in the Colorado Front Range and found that both hydromulch and straw mulch reduced sediment production by 90 percent in the first year following a wildfire, supporting our application of ERMiT straw mulch calculations to the potential effectiveness of hydromulch. Hubbert (2005) monitored treatment effectiveness for two fires in Southern California. In the first case study, the hydromulch was completely ineffective, due to high winds carrying away the treatment. In the second, hillslopes treated at 50 percent coverage had reduced erosion rates of approximately half of expected. Still, many managers believe that mitigation treatments, such as hydromulching, have high a potential for reducing post-fire erosion. However, until efficacy metrics can be determined with some high level of accuracy, it is only possible to estimate the effectiveness of mulching within one order of magnitude.

Limitations of Analysis

ERMiT is an event-driven tool that predicts the amounts of sediment mobilized by surface erosion and is not designed to predict total erosion over a season. Thus, if more than one large rainstorm were to occur in a single winter, it would be important that any sediment accumulated in the first storm be removed promptly from vulnerable reaches. ERMiT is unable to consider antecedent moisture, so there is no difference in the output between a 10-year storm event occurring in March after several low intensity rain storms and that same storm as one of the first rains of the winter. Also, since local climate files are created based on a 66-year period of historical data, ERMiT results for larger storms (i.e. 25-, 50-, and 100-year storms) are less likely to be included in actual historical data. Therefore, estimates of sediment supplies for large storms are likely to be outside of the local instrumental record, and therefore are more difficult to assess. Furthermore, this analysis assumes that all of the sediment delivered to the channel is transported downstream, possibly overestimating possible post-fire erosion. Despite these approximations, fire area managers utilize the tool to support a precautionary approach to management.

The most significant factors in sediment delivery rates are rainfall and storm event frequency and intensity, along with soil burn severity (see Appendix 10.2). ERMiT is extremely sensitive to fire intensity, as a high intensity burn can produce double the sediment volume as a low intensity burn. This project only varies the acreage burned within a watershed, as opposed to modeling fire intensity. Fire intensity varies widely within a burn area and is dependent on the residence time of the fire in any given place. The Gap Fire had areas of low, moderate and high intensity burns (BEAR 2008). Because of the spatial heterogeneity of fire intensity, our analysis assumes a potential fire in Mission Creek watershed will have a moderate burn intensity This decision prevents examination of the affects of soil burn intensity on erosion and runoff. However, the fire size variation does allow for the comparison of two wildfires in Mission watershed with similar burn intensity to the 2008 Gap Fire, which burned on average at a moderate intensity. This technique furthers our goal of utilizing the Gap Fire to determine representative parameters for our modeling tools.

In order to keep the user interface simple, ERMiT has a coarse spatial analysis of soil texture, a factor which may greatly influence sediment delivery rates. The parameters within ERMiT control multiple parameter “sets” in the Water Erosion Prediction Project (WEPP) model. These sets include soil characteristics such as soil depth, cohesion, etc, which may not accurately represent the characteristics of Mission watershed due to the coarse spatial analysis of the WEPP model. Additionally, the predictions of erosion by ERMiT and WEPP are for soil covered hillslopes only, and don't account for the large areas of exposed bedrock in the upper watershed

Finally, ERMiT was designed to predict sediment delivery probability in a watershed fitting the general description of Mission. It is not designed to capture the unique dynamic processes within particular watersheds (Robichaud *et al.* 2007). In order to capture a more accurate view of erosion processes in Mission Creek watershed, a spatial analysis using Digital Elevation Model (DEM)-based flowpath methods could be more appropriate, but would still be limited by the lack of local measurements for calibration since measurements of sedimentation resulting from fires in this region are rare.

6.2 Shallow Landslide/Debris Flow Model (SHALSTAB)

The Shallow Landsliding Stability Model (SHALSTAB) is a decision support tool designed to spatially assess the potential for sediment production from unstable slopes under different watershed conditions (Dietrich and Montgomery, 1998). Depending on the size of failure, landslides can damage property, roads, landscapes, and stream channels. In order to prevent this damage, there is a need to recognize areas of high risk, avoid actions that promote or exacerbate landslide conditions, and prepare for the occurrence of unstable hillsides. Although natural, the conditions leading to landsliding can also be affected by human actions such as development and wildfire. With SHALSTAB, the slope instability is spatially displayed under different management scenarios by changing the input parameters to the model.

SHALSTAB incorporates the slope as well as the curvature of the hillside to determine areas where soil and water will converge and accumulate, creating conditions prone to landsliding. The model also incorporates soil properties include the internal friction angle (which depends largely on soil texture), depth, bulk density, and soil/root cohesion to identify potentially unstable sites. These areas are represented by a certain value of T, transmissivity, or the ability of the subsurface to convey the water downhill, which can then be compared to q, the intensity of a rainstorm. The SHALSTAB model calculates the ratio of q/T, the log of which is a measure of the site's susceptibility to failure, with a larger ratio indicating a higher vulnerability to landsliding. For specific information regarding the chosen inputs to SHALSTAB, please see Appendix 10.3.

Scenario Analysis

Cohesion, which depends slightly on clay content and dominantly on root reinforcement, is an important input to the SHALSTAB model, especially as it represents a soil characteristic impacted by natural or human initiated fires that decrease the root strength of hillslope vegetation (Dietrich and Booker 1995). Soil depth is variable throughout both watersheds, and the soils data classifies broadly with ranges of depths. Most of Mission Creek watershed is classified as “0-60 cm” depth, so a low, medium, and high estimate of soil depth was used to observe the effects of fire under different soil characteristics. Since SHALSTAB can only calculate slope instability with one input for the entire watershed, maps were created for a number of combinations of soil cohesion and soil depth (Table 6-D).

Table 6-D: SHALSTAB fire scenarios in Mission Creek watershed with different combinations of soil depth (to include the range of soil types in the upper watershed) and cohesion (representing a change in the soil structure due to burning of roots).

Code	Soil depth, Cohesion	Friction Angle	Soil Density	Soil Depth	Cohesion
SH	Shallow, High	*35*	*1450*	*0.25*	*1000*
SM	Shallow, Medium	*35*	*1450*	*0.25*	*500*
SL	Shallow, Low	*35*	*1450*	*0.25*	*0*
MH	Medium, High	*35*	*1450*	*0.875*	*1000*
MM	Medium, Medium	*35*	*1450*	*0.875*	*500*
ML	Medium, Low	*35*	*1450*	*0.875*	*0*
DH	Deep, High	*35*	*1450*	*1.5*	*1000*
DM	Deep, Medium	*35*	*1450*	*1.5*	*500*
DL	Deep, Low	*35*	*1450*	*1.5*	*0*

SHALSTAB Results

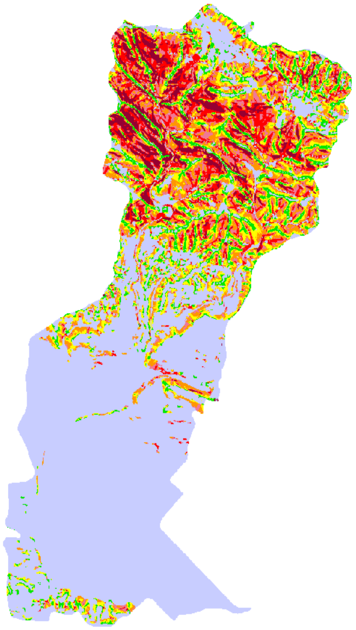


Figure 6-D: Baseline SHALSTAB scenario (MM) (see Table 6-D)

The baseline pre-fire scenario of medium soil depth and medium cohesion is represented in Figure 6-D. Each SHALSTAB trial produces a GIS layer of hillslope instability, with very stable soils shown as light blue and chronically unstable soils in dark red. SHALSTAB consistently predicts stable soils in the lower watershed and considerably variable conditions in the mid-upper watershed, depending on model inputs. SHALSTAB presents “chronically unstable” hillslopes (shown in dark red) as those with a log q/T of -3.4 or more, which corresponds to a q/T ratio of less than 0.00040. A low q/T ratio suggests features that are prone to failure due to thick soil. This is true even for low-intensity storms, and these areas present a capacity for high water pressures and a high water table, with properties that may trigger a debris flow. Lighter red values are only slightly more stable, representing a q/T ratio of 0.00079, and are much more common throughout the areas of relief between ridges. Note that most scenarios depict ridges in a lighter yellow or blue color. Those q/T values, above 0.003, represent exposed bedrock or soil profiles that are thin because of gravitational movement of soil downhill and away from such formations. The lower watershed is generally stable (blue) in every scenario because it has a low gradient, and is thus only rarely affected by small-scale landsliding near stream reaches, where slopes are higher and sub-surface water converges.

Decreasing cohesion increases slope instability, especially in areas that are already prone to landsliding (converging slopes, canyon margins, and bedrock hollows). Deeper soils are more likely to collapse, and shallow soil conditions present a lower hazard for landsliding. However, even in the shallow soil scenario, decreasing the cohesion to a value of zero creates conditions for hillslope instability, especially in the steep upper watershed, because thin soils can be saturated by small rainstorms.

It is possible to compare the output of SHALSTAB according to the percent of the watershed that is calculated to contain a certain level of instability for different soil depth and soil cohesion scenarios (Figure 6-E). Fifty percent or more of the Mission Creek Watershed is considered stable; this is mostly in the lower watershed areas where conditions do not lend to landsliding. The proportion of the watershed that is considered chronically instable increases under low cohesion conditions, especially for shallow soils.

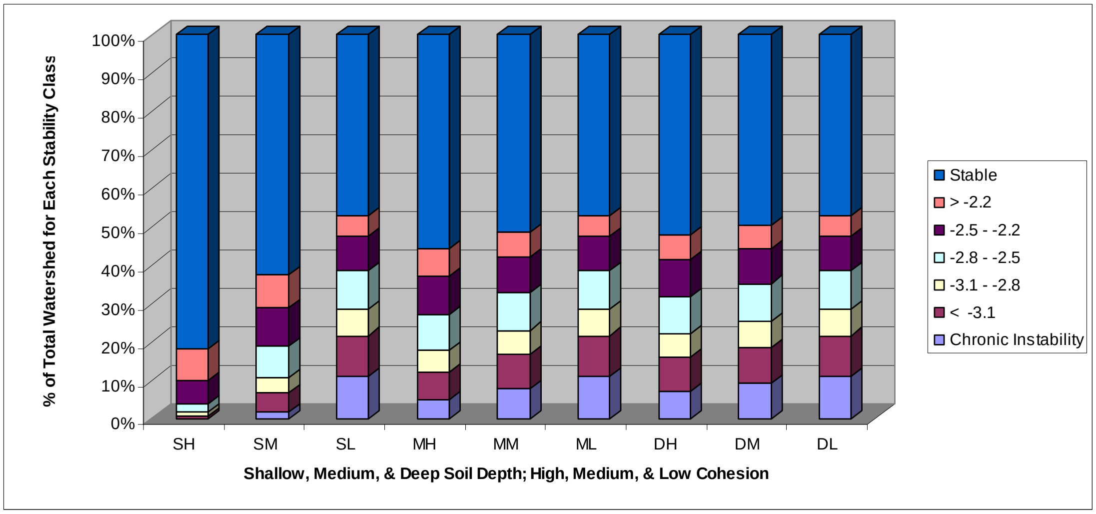


Figure 6-E: Percent of Mission Creek watershed exhibiting a range of stability classes. The percent of the watershed with stable soils decreases under post-fire conditions. For scenario codes (x-axis), see Table 6-D.

Figure 6-F compares the SHALSTAB output for the baseline pre-fire scenario (of medium soil depth and typical cohesion values) and the same watershed under post-fire conditions. The dark red areas with chronically unstable soil increase by 53% in the post-fire scenario, primarily in the upper and middle watershed. The greatest increases in instability were calculated in the steep slopes of the northwest corner of the watershed in the Los Padres National Forest. A second area of concern is the residential area of Mission Canyon in the middle watershed, where small localized debris flows could affect structures and property.

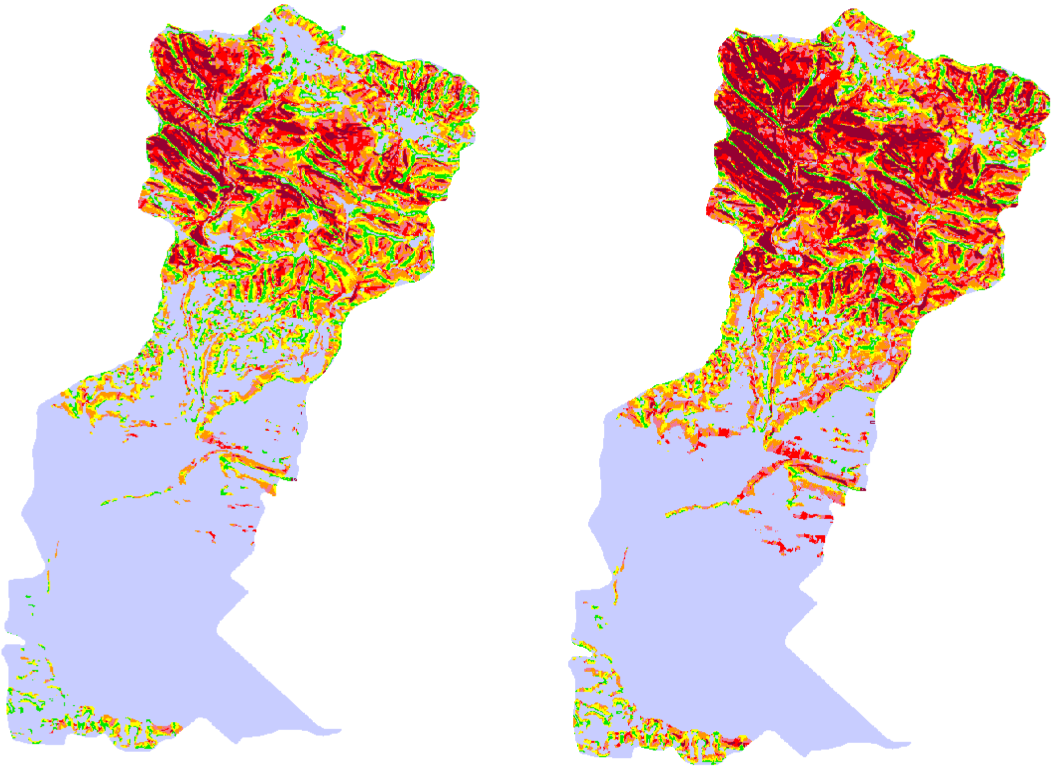


Figure 6-F: Comparison of SHALSTAB output for Mission Creek watershed under pre-fire (left) and post-fire (right) conditions, keeping soil depth constant. Areas of concern are shown in dark red, mostly in the mid and upper watershed.

Exposed bedrock, estimated at 2-9 percent of the upper watershed, is not captured in SHALSTAB modeling. Nevertheless, SHALSTAB indicates that we should expect some expansion of chronic instability, especially on the shallow soils of the steep upper slopes. In particular, the 55 percent of the basin covered with stable, shallow soils under chaparral is likely to diminish to 47 percent of the basin when the root cohesion is removed by burning.

The results suggest that some collapse of soil profiles is likely to happen in the northern, remote parts of the watershed in large rainstorms, which would add significantly to the sediment yield predicted by ERMiT for water erosion alone as landsliding abruptly removes the entire soil profile from a hillside. It is not so clear whether the failed material would evolve into debris flows that could become destructive because of their speed, density, and viscosity. Debris-flow formation would require extensive, simultaneous collapse of soil profiles that would overload the capacity of streamflow to dilute the sediment and carry it downstream. This condition would require extensive heavy rain. However, some degree of debris-flow formation cannot be ruled out, and it would be wise for the flood-control district to establish debris-flow sensors in the upper reaches of the canyon to provide automated early warning after a fire.

The SHALSTAB analysis identified areas of the Mission Creek watershed that are prone to chronic instability, and modeled the potential effects of fire on these areas. Although little quantitative information was gathered in this process, understanding the potential for shallow landsliding was an important component of forming an understanding of watershed processes under burned and unburned conditions.

Limitations of Analysis

SHALSTAB only identifies areas prone to shallow landslides and cannot predict whether a slide will occur or its magnitude. It is also unable to estimate the volume of sediment delivery that may be expected. Therefore, the results from this model are not included to support estimates of sediment delivery in upper and middle Mission Creek Watershed. However, the application of this model to mission creek suggests that one should expect some enhancement of landsliding and therefore of sediment production over and above the surface erosion after a fire.

Additionally, the effects of fire on a watershed are not homogenous, and the model does not account for spatial variance. Furthermore, the model is not equipped to use spatial soils data to change input parameters on a finer scale, and can only accept inputs for the entire watershed as a whole. This project used inputs that were considered realistic for the scenarios in the upper and mid watershed, where debris flow risk would create the greatest hazard, and used soil data specific to those areas.

Finally, the output of SHALSTAB does not allow for prediction of the fate of the released colluvium. For example, the sediment could travel as a debris flow through stream channels, causing damage and flooding to downstream communities. Alternatively, the soil could slide downslope and be contained in natural catch basins, only affecting local geomorphologic processes or individual structures. For this reason, this project does not rely on SHALSTAB to provide any quantitative support for the estimates of debris potential.

7. ANALYSIS OF POST-FIRE RISK

7.1 Flood Risk

Every storm and fire scenario this project examined would create flooding in some part of Mission Creek, some potentially causing discharges larger than any in recorded history. Except for one constriction, Mission Creek is designed to carry discharges from the 15- to 20-year storm. One area of Mission Creek near the Montecito Street Bridge will flood with discharges greater than 1,500 cfs, but most reaches of the creek can contain up to 3,200 cfs (FEMA 2005a). HEC-HMS results show a 2-year recurrence interval storm on dry soils would create 3,360 cfs after a fire burning 25 percent of the watershed.

Not only do the more probable, smaller precipitation events create discharges that will flood overbank, but the probability of large, destructive floods increases significantly. As discussed in Chapter 5, the likelihood of discharge comparable to that of the 100-year flood is four to twenty times greater following a fire, depending on the size of fire and antecedent moisture conditions (Figure 7-A).

In 1995, an intense storm flooded downtown Santa Barbara when discharge in Mission Creek reached 5,120 cfs, causing $4,611,300 of damage and covering most of the flooded area with approximately 1 foot of fine sediment. At least 300 homes were damaged in the floodwaters, which were estimated to be at least 3 feet deep in some areas (USACE 2000b). Discharge of this magnitude is typically associated with a 50-year flood, but results show similar discharge would occur after a large fire in a 2- to 5-year storm with wet antecedent soil moisture. This translates into a flood of this magnitude being more than ten times more likely when 50 percent of the upper watershed is burned.

This significant increase in flood risk after fire presents a difficult management problem in an urban channel with limited capacity. For the last decade, the City of Santa Barbara, Santa Barbara County Flood Control and Water Conservation District, and the U.S. Army Corps of Engineers have planned infrastructure improvements to increase the conveyance capacity of Mission Creek (USACE 2000b), but these projects have yet been implemented. The risk of flooding to downtown Santa Barbara will decrease significantly in fire and non-fire years when these projects are completed.

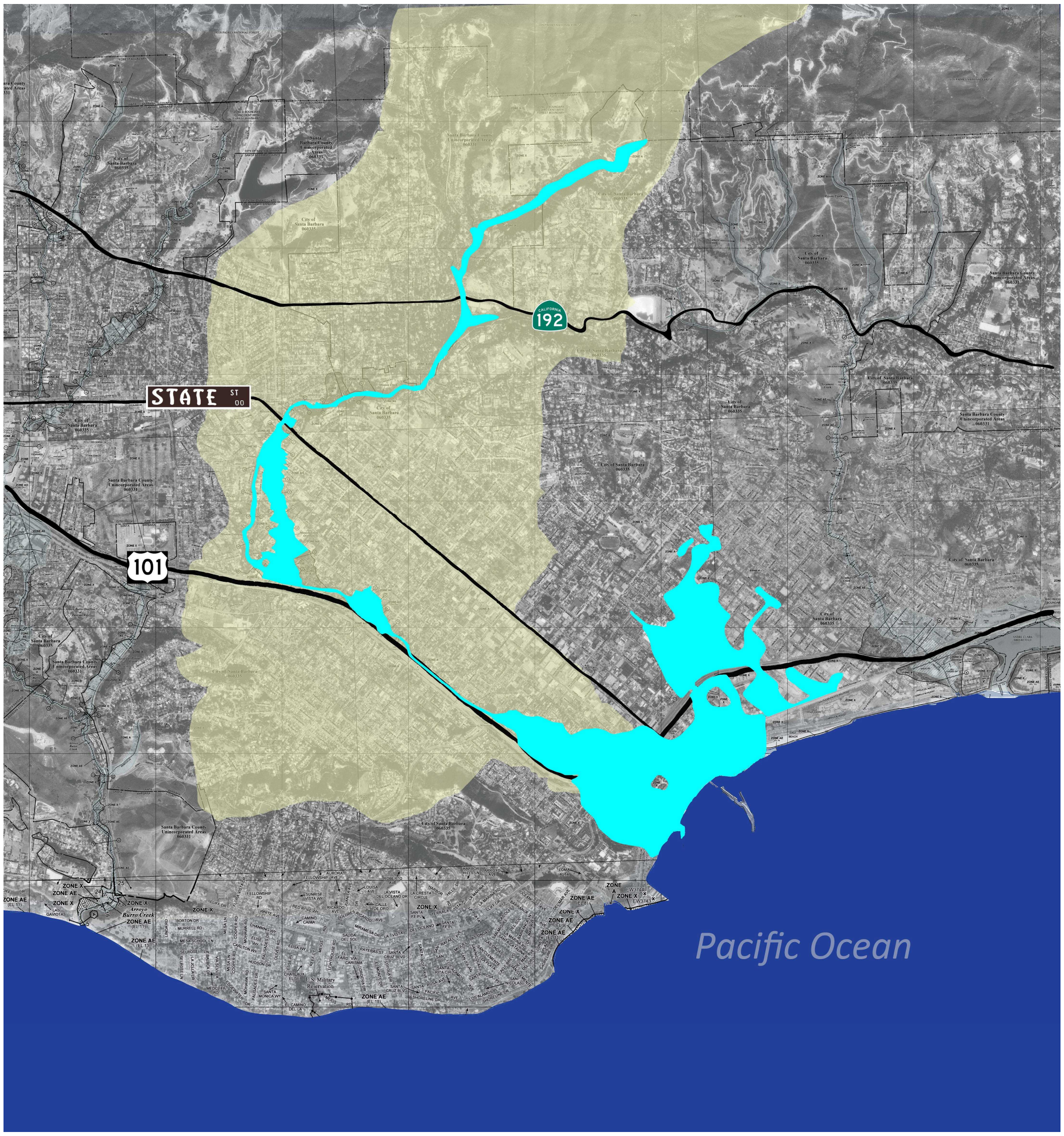


Figure 7-A: 100- year Floodplain of Mission Creek is outlined in bright blue in the Mission Creek Watershed (yellow background). The discharge that causes this area to flood, which would occur in a 100-year recurrence storm, is predicted to be created in a 25-year storm after a small fire (dry antecedent moisture) or a 5-year storm after a large fire (wet antecedent moisture).

(Source Data: FEMA, ESRI)

7.2 Effects of Sedimentation on Flooding

Although estimation of flood risk and sedimentation risk are valuable results separately, the effects of sedimentation and flooding should be considered together in post-fire risk planning. The hazards of flooding and erosion are both driven by the probability of a certain size of rainstorm occurring in the first year after a fire and do not operate independently. In any given rainstorm, the amount of sediment the creek can transport is determined by the magnitude of the flow. As the slope of the channel decreases in the lower reach of the creek, flow velocity decreases, allowing sediment to drop out of the water column and aggrade the channel bed. Sediment accumulation on the bed of the channel reduces channel capacity and exacerbates flooding problems.

Sediment delivery estimates (from ERMiT) and runoff estimates (from HEC-HMS) were used with calculated transport rates to estimate the risk of sedimentation within the channel resulting from storms with 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals. Calculations assume all sediment delivered to the Creek is either deposited in one of the two existing sediment basins or transported approximately 4 miles to the lower reaches. The sediment basins were designed to capture 15,900 yd^3 of sediment for the western basin (Mission) and 8,300 yd^3 for the eastern basin (Rattlesnake Creek). However, they are currently only maintained to a capacity of 4,100 yd^3 and 3,000 yd^3, respectively (Maureen Spencer, SB County Flood Control, pers. comm.). Calculations of sediment mobility indicate that almost all particles likely to enter the stream network from burned hillslopes would remain mobile in the upper 4 miles of the channel network. Coarser particles would not travel as quickly as the water, and some fraction of gravel may be temporarily stranded between floods as gravel bars within the upper watershed. No culvert blockages were assumed to occur that would interrupt flow and sediment transport. Sediment basins were assumed to have been excavated to their full design capacity in the first winter following a fire, as this would capture the most sediment and reduce downstream risk.

Sediment accumulation was estimated for a 1,100 ft (335 m) flood-prone reach in downtown Santa Barbara, approximately between the Haley St. and Gutierrez St bridges (Figure 7-B). The upstream boundary of this reach (cross-section 2) is a break in channel slope that decreases gradient as compared to upstream. The downstream boundary is approximately Gutierrez Street (cross-section 3), where flood depth in the channel decreases significantly as shallow water spreads over a wide area of downtown Santa Barbara. As sediment accumulates and decreases channel capacity, the amount of water flowing overbank increases.

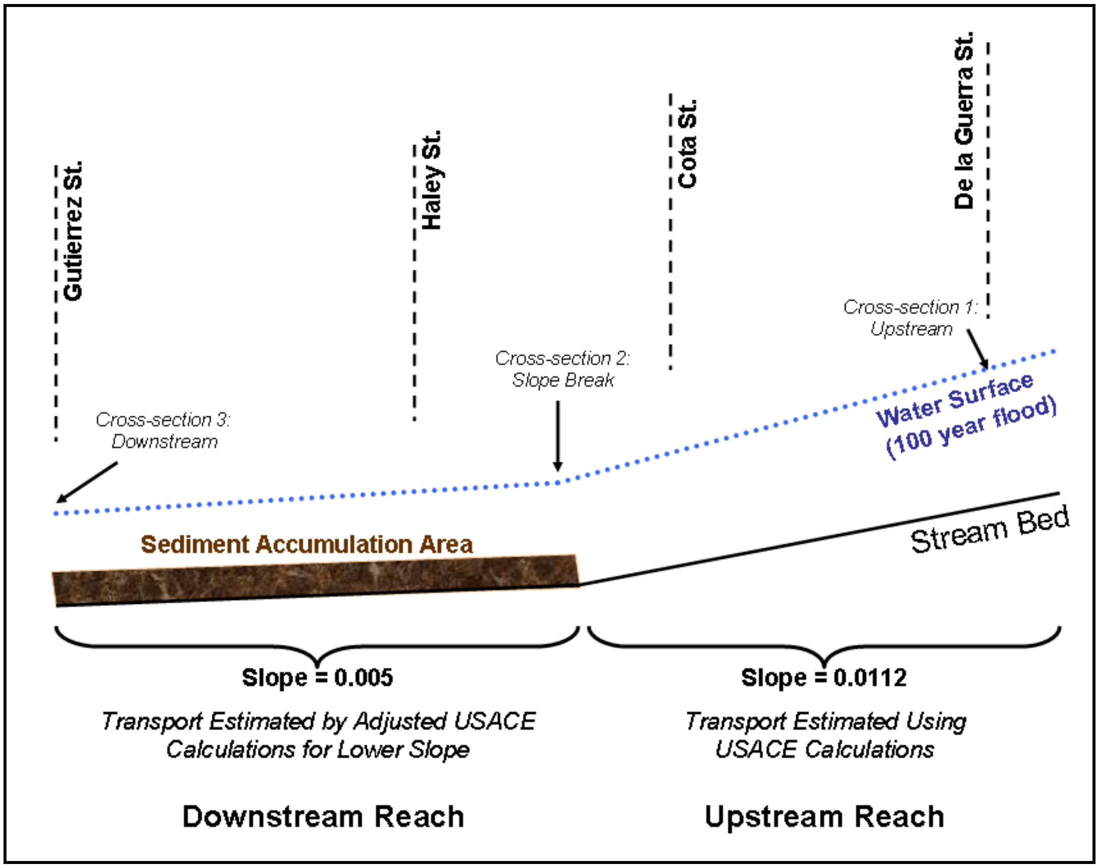


Figure 7-B: Sediment Transport Study Reaches (Not to scale). The upstream reach (between cross-section 1 and 2) was assumed to have constant sediment transport capacity as estimated for cross-section 1 by USACE. The downstream reach (between cross-section 2 and 3) has lower slope and therefore decreased sediment transport capacity, and USACE estimates were adjusted to represent this change. ERMiT-calculated sediment inputs were assumed to enter the upstream reach, and the difference in sediment transported in the upstream and downstream reaches was calculated. The difference was assumed to accumulate in the downstream reach.

A reach with greater, relatively constant slope was designated upstream of the slope break, beginning at approximately De la Guerra St. (cross-section 1), and ending at cross-section 2. The difference in slope between the upstream and downstream reaches creates a difference in sediment transport capacity. Sediment that is no longer transportable accumulates on the bed in the downstream reach. This change in transport capacity is the basis for sediment accumulation estimates in this reach of Mission Creek.

Channel slope at each of the cross-sections was determined using water surface elevation estimates of the 100-year flood (FEMA 2005a). The slope of water surface elevation was estimated to be 0.0112 for the upstream reach (between cross-sections 1 and 2) and 0.005 for the downstream reach (between cross-sections 2 and 3). Sediment transport capacity estimates made by the U.S. Army Corps of Engineers (USACE, Appendix 10.1.5) were available for cross-section 1. Sediment transport rates were presumed constant over the upstream reach, assuming constant channel slope, geometry, and roughness. Sediment transport capacity for cross-section 3 was estimated by adjusting USACE estimates for reduced slope.

Total sedimentation in the reach was calculated as the difference in transport capacity between the upstream reach and the downstream reach. The comparison is made for qualitative illustration only as the USACE prediction is untested. Although water surface slope is the main driver of sediment transport capacity, smaller influences on sediment transport are also made by changes in channel width, depth, and roughness.

Gravel bedload transport was estimated by the USACE using the Meyer-Peter-Müller equation, which has been calibrated in flumes for estimating transport in gravel-bedded streams with an unlimited supply of gravel. Transport of sand-sized particles was estimated using Toffaleti’s equation, which was originally developed for large, low-gradient rivers. These equations were calibrated under much different stream characteristics than small, steep Mission Creek, but they provide an index of probable changes in transport conditions and therefore are valuable for indicating spatial patterns of sediment transport change and sedimentation, even if the absolute values predicted are not reliable.

Results of the analysis showed potential gravel accumulation in the reach between Haley St. and Gutierrez St. to be 0 to 2 feet, with most likely accumulation of less than 1 foot in depth. Predicted aggradation increases with storm size for storms smaller than the 10-year recurrence storm, then decreases with larger storms as transport capacity of larger discharges exceeds supply (Figure 7-C). Using channel geometry and Manning’s equation, it was estimated that 1 foot of channel bed rise due to aggrading sediment in this reach would result in a 10 percent decrease in channel capacity at cross-sections 2 and 3, increasing the magnitude of floods in this part of Mission Creek watershed. Because all storms analyzed would cause flooding in this reach (discussed in Chapter 5), only the stage and extent of flooding, not the probability, will increase significantly.

The transport calculations were not extended to the mouth of Mission Creek because the USACE calculations of flood profiles do not take account of the state of the tide, which would reduce the water-surface slope and velocity of the creek for some distance upslope at high tides. If a flood occurred at high tide, it is likely that the transport capacity of the creek in the vicinity of Cabrillo Boulevard would be reduced and sediment would also be deposited there. Sediment accumulation would exacerbate already intensified flooding from high tides (FEMA 2005a).

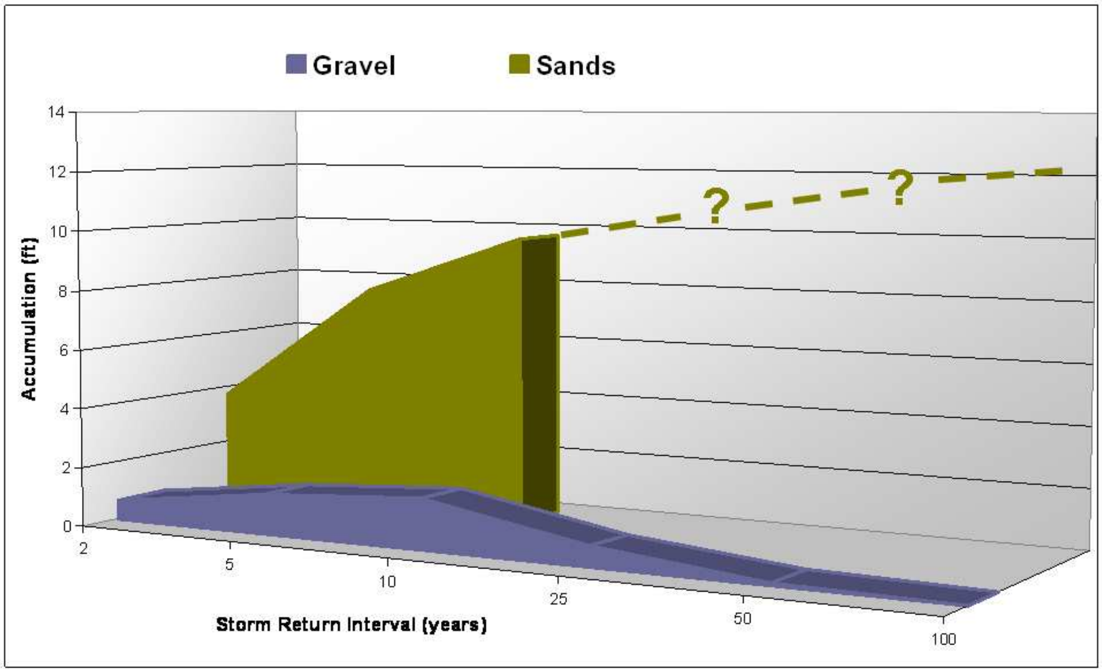


Figure 7-C: Potential sediment accumulation in Mission Creek, Downtown Santa Barbara between approximately Haley and Gutierrez Streets, as calculated by modifying estimates made by the U.S. Army Corps of Engineers and the Federal Emergency Management Agency. The predicted accumulation exceeds the channel depth for storms equal or greater than the 25-year event. For reasons discussed and interpreted in the text, the results are meant as qualitative illustration only of the potential problem. However,, results indicate an increased risk of sediment accumulation and therefore overbank flooding along lower Mission Creek in post-fire floods.

Estimates of gravel accumulation are likely to be more accurate than those for sand-sized sediment because the Toffaleti equation was applied by the USACE in conditions very different from its range of calibration. Results of sand accumulation of 4 to 19 ft were calculated for 2- to 100- year events. The magnitude of accumulation may be overestimated because of uncertainties in the amount of sediment input to the reach (the ERMiT calculations predicted rates of sediment loss in the 100-year flood are beyond those yet measured in the region) and in the use of Toffaleti's transport equation, but a trend of increased accumulation with increased flood size is notable. Sediment accumulating in the reach will have higher proportions of fine sediment (sands) than coarse sediment (gravels). Also, as storm size increases and a larger proportion of water floods overbank, some of this finer sediment would disperse with floodwater rather than aggrading on the bed, as seen in the 1995 flood. Even interpreted qualitatively, however, the calculations suggest a serious risk of sediment accumulation and enhanced overbank flooding along lower Mission Creek in post-fire floods.

Sand and gravel accumulation in lower Mission Creek is assumed to be delivered by the surface erosion process predicted in ERMiT. However, mass wasting events such as landslides and debris flows can also provide a significant amount of sediment to the channel and exacerbate flooding problems. The risk of debris flows is greater after a fire but they are less likely than surface erosion and more difficult to predict. SHALSTAB only indicates an extension of the areas which are more likely to produce collapsed debris, and can not quantify whether or how much of the debris will evolve into debris flows that could reach lower Mission Creek. For this reason, debris-flow risk is not included in overall risk analysis or mitigation assessment

8. RECOMMENDATIONS

Local management of post-fire risk requires planning and decision making at multiple levels of government and within communities (as discussed in Section 3.5). The methods and results of this project will contribute to future predictions of post-fire flooding and sedimentation in Mission Creek and similar watersheds. Furthermore, this information may improve long term environmental planning for post-fire winters and emergency situations in Mission Canyon and downtown Santa Barbara.

The information generated from this project assists in evaluating the appropriateness and effectiveness of various emergency post-fire measures for Mission Creek watershed or similar areas. More importantly, local officials can use the results of this study for management decisions and planning actions well before a wildfire occurs. Planning for the inevitable fire in the upper watershed by understanding the potential magnitude of risk associated with increased erosion, flooding, and debris flows can reduce the need for extensive emergency watershed protection measures. Recommendations focus on both specific mitigation actions to reduce runoff or sediment delivery to downstream areas and on coordinated emergency and long-range planning for local agencies and community leaders.

The results of this project support the following recommendations:

- **Emergency Post-Fire Actions**
    - A. Excavate sediment basins to maximum capacity (if not completed before the fire)
    - B. Increase channel capacity (emergency channel clearing and debris control)
    - C. Stabilize hillslopes by applying hydromulch
- **Long Term Planning Actions**
    - D. Increase channel capacity (strategic infrastructure and flood control projects)
    - E. Incorporate post-fire risk into city and county General Plans
    - F. Incorporate post-fire risk into Winter Storm Emergency Response Plans
    - G. Establish public information systems

8.1 Emergency Post-Fire Actions

Post-fire management actions include physical barriers on hillslopes or in channels to reduce the volume and rate of runoff and erosion at the source. Additionally, many jurisdictions perform emergency dredging or excavation of sediment basins to increase capacity and prevent debris accumulation and flooding downstream. City and county agencies may undertake any combination of locally appropriate measures during the interval of time between the fire and the first rains of the winter. However, since emergency mitigation measures can be very expensive, the efficacy of such actions needs to be considered on a watershed basis.

Hillslope treatments vary in their effectiveness for an area like the upper Mission Creek watershed. Some measures only retain sediment for small areas, thus requiring labor-intensive application in inaccessible portions of the watershed. Furthermore, contour-felled logs, trenches, and silt fences, which are installed on the hillslope parallel to the channel, need regular maintenance for continued performance throughout the winter. Erosion control fabric has potential negative impacts on vegetative re-growth and ground-dwelling animals (Robichaud *et al.* 2000). As a surface treatment, seeding is not recommended due to the introduction of non-native species in an environmentally sensitive chaparral habitat. Another surface treatment, hydromulching, is discussed in contrast to straw mulching in Section 6, but is a generally accepted treatment for local mountain areas. Channel treatments include channel clearing, debris racks, and sediment basins. Debris racks catch large debris like boulders and logs and prevent them from plugging constrictions in the channel. Debris racks are effective at catching larger objects, but do not address the problem of sediment accumulation. Check dams may be placed in the middle watershed on moderate gradients and are effective in slowing the movement of gravel and sand-sized particles downstream.

After the Gap Fire, Santa Barbara Country Flood Control engaged in channel clearing, installation of debris racks and maintenance of sediment basins and the Goleta Slough. Furthermore, the largest expense of resources was dedicated to the application of aerial hydromulch (Santa Barbara County 2008). It is expected that similar or identical measures would be taken in the event of a fire in Mission Creek watershed. The intent of this portion of the project is to contribute to existing emergency response plans by prioritizing the most effective actions to mitigate the potential impacts of erosion and flooding. Three emergency post-fire actions are discussed: expanding sediment basins, initiating channel clearing, and hydromulching of exposed hillsides of the upper watershed. Alternative channel and hillslope treatments were considered but deemed less appropriate for the region.

A. Empty Existing Sediment Basins

Consideration of increased post-fire erosion and debris production in the upper Mission Creek watershed requires an evaluation of existing sediment basins. According to calculations with ERMiT, the two sediment basins in the eastern and western tributaries of Mission Creek are inadequate to capture the expected sediment delivery from even a 2-year storm (50 percent probability of occurring in a year) following a small fire. Although both sediment basins are excavated periodically, neither is cleared to the original design volume. Table 8-A displays the current and design capacities of the eastern (Rattlesnake Canyon) and western (Mission Creek) sediment basins in relation to the predicted volume of sediment delivered under different storm conditions. Rattlesnake Canyon basin receives a similar amount of sediment to the Mission Creek basin, although the capacity is much less. The current capacity is significantly smaller than the design capacity for both basins, and design capacity fails to contain sediment production from a 2-year storm after a large fire.

Table 8-A. Sediment volume (yd3) delivered to two sediment basins in Mission Creek Watershed.

Watershed	**Sediment volume for a 2-yr storm in large fire**	**Sediment volume for a 5-yr in large fire**	**Design capacity of debris basin**	**Current capacity of debris basin**
Rattlesnake	25537	76696	8300	3000
Mission	26440	76210	15900	4100
Total	51977	152906	24200	7100

While sediment basin excavation can occur quickly under emergency post-fire situations, supplemental effort and time may be needed to remove enough sediment to provide adequate debris storage capacity. Therefore, local jurisdictions should intensify their sediment basin maintenance programs to achieve complete, rather than partial, sediment removal after a fire.

B. Increase Channel Capacity: Short Term

The primary mitigation activities completed by Santa Barbara County Flood Control to protect the City of Goleta from post-Gap Fire flooding included the removal of sediment and riparian vegetation from the lower watershed channels (Santa Barbara County 2008). The possibility of 1-2 feet (0.3-0.6 m) of additional sediment accumulation in the lower reach of Mission Creek (and possibly more upstream of culverts) supports this mitigation activity.

In addition to sediment accumulation and vegetation growth, large woody debris and recently burned materials can become trapped under bridge crossings or in culverts and exacerbate flooding conditions. Therefore, the installation of emergency debris retention structures such as K-rails and debris racks in accessible areas of the middle and upper watershed, above urban areas where flooding may occur from accumulation of large debris.

C. Stabilize Hillslopes by Applying Hydromulch

As described in Section 6, the Erosion Risk Management Tool (ERMiT) has the capability of estimating the relative decrease in sediment production using various mitigation treatments, including mulching. Erosion may decrease by up to 90%, and it is most effective in small to moderate storms.

Mulching is the most widely applied post-fire mitigation measure on U.S. Forest Service (USFS) land in Southern California. According to the USFS, a fire in upper Mission Creek watershed would necessitate the application of straw or hydromulch on burned hillslopes due to the presence of residential and commercial areas downstream of forest lands. Based on BAER team recommendations, the entire Gap Fire burn area in the Los Padres National Forest (including much of the San Pedro watershed) was sprayed from the air with hydromulch at a cost of $3,200/acre or around $4 million total (Mary Moore, USFS, pers. comm.).

8.2 Long Term Planning Actions

Emergency responses to wildfire are necessarily short-term and temporary in nature. Post-fire emergency sediment and vegetation removal may slightly increase channel capacity or reduce debris accumulation, but will not generate permanent, sustainable forms of management. An understanding of the unique risks associated with accelerated flood and sedimentation processes after a fire must be included in long-term planning strategies. These plans promote awareness and community preparedness for flooding and possible debris flows, allowing residents adequate time to protect their structures from damage.

A. Increase Channel Capacity: Long Term

The risk of increased flood magnitudes as a result of fires in the upper watershed enhances the value of proposed engineering changes to increase the flood conveyance capacity of lower Mission Creek. Santa Barbara County Flood Control and the US Army Corps of Engineers are involved in a thirty-year effort to increase flood capacity in lower Mission Creek. This project would increase flood capacity from a minimum of 1500 to 3400 cubic feet per second, including a weir/culvert system to divert storm flows into a newly-constructed concrete channel under the railroad (Matthew Griffin, SB Flood Control, pers. comm.). While this is an important step in flood management in downtown Santa Barbara, these improvements will still only accommodate flows for a 2-year storm after a small fire, regardless of the added risk of sediment or debris accumulation in the channel. Still, the overall risk reduction potential of such projects would be considerable since smaller storms occur with more frequency.

B. Incorporate Post-Fire Risk into General Plans

The City and County of Santa Barbara create General Plans that outline long term management of development and land use. Plans are created and updated through the cooperative efforts of local agencies and community organizations, and may be tailored for specific communities. Estimates of the type and magnitude of risks posed by post-fire conditions should be included in planning elements, especially for areas with high vulnerability for flooding or debris flows. Government officials are responsible for using detailed local information to determine the acceptable thresholds of risk, such as the storm size that should be prepared for during planning of public works projects. For example, the Mission Canyon Community Plan has the capacity to address the increased risk of debris flows in this community after a fire. This could be accomplished by the identification of unstable hillslopes through geographic analysis of the watershed with programs such as SHALSTAB.

Some actions to be included in General or Community Plans may include:

- Assessment of access roads, utilities, or structures for susceptibility to post-fire flood and debris flow damage.
- Localized protection of infrastructure through sand bags, roadside drainage expansion, or the erection of temporary structures k-rails to route sediment around valuable assets in the case of a debris flow.
- Long term managed retreat from highly vulnerable areas through the reclamation of property and removal of structures in the immediate vicinity of Mission Creek.
- Emergency management plans attentive to the specific issues surrounding post-fire watershed conditions (i.e. debris flows, erosion, and increased runoff)

F. Incorporate Post-Fire Risk into Storm Emergency Response Plans

To facilitate the most efficient response to post-fire hazards, the Santa Barbara City and County Offices of Emergency Services should streamline post-fire emergency management and collaborate with the other agencies in creating a county-wide Winter Storm Emergency Response Plan that addresses the increased risk of flooding and debris flows in post-fire years. This plan could address post-fire mitigation, but would primarily manage emergency response actions during a hazardous storm event. Evacuation routes and flash flood or debris flow warning systems and can be managed efficiently and effectively for identified vulnerable areas.

Topics to be addressed in Winter Storm Emergency Response Plans include:

- What size storm should be considered the threshold event in planning for a post-fire rainy season? How does this affect flood watches or warnings and evacuation planning? How can the approach of such a storm be tracked in communication with local weather forecasting services?
- During what storm events (post-fire) are evacuation routes threatened? Are there alternative routes which are preferable, or is action needed to secure a safe route out of the area?
- What areas are most at-risk given a certain storm event and should be prioritized for emergency protections or evacuation?

G. Information Systems

Post-fire risk management is facilitated by interagency communication and information dissemination to the public. Recent and ongoing advances in information technology provide easily accessible and centralized information to citizens in order to improve public services in their communities. Such repositories improve public education and awareness of post-fire risk, and can prove extremely useful during emergency management scenarios.

Information needs fall into two categories, ongoing information needs and emergency information needs. The first is the constant availability of weather forecasts (temperature, winds, etc) as well as assessments of local watershed hydrology and erosion risk throughout the fire and rainy season. This could take the form of a centralized webpage run in coordination with multiple local agencies and with the participation of community members. The goal is to provide a forum for information sharing, as well as to increase transparency in decision-making processes. Citizens can gain an understanding of risk within their area, as well as actions they might take in advance to mitigate risk.

The second need is the immediate availability and update of data in emergency situations, such as the outbreak of a wildfire or the advent of a large (greater than 2-year recurrence) storm in the winter following the fire. During the Tea Fire, a graduate student from the Geography Department of the University of California, Santa Barbara used the Google Maps interface to inform citizens about the spreading of the fire, shelter and hospital locations, mandatory and recommended evacuation areas and other real-time information. Though provided by a private individual with no connection to emergency services, this proved to be the single best source for spatially explicit information about the fire during the burn itself. This type of information system would require the use of a geographic interface, like Yahoo! Maps, Google Maps or Google Earth and a staff person on-call throughout the fire and rainy season with the ability to acquire and disseminate data through the internet.

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APPENDIX 10.1: HEC-HMS

Mission Creek watershed was divided into 17 sub-basins using the Pre-Pro extension to ArcMap GIS, which uses 10-meter digital elevation models to delineate sub-basins and stream segments. Five minute rain gauge data, parameters representing the condition of the watershed, and stream channel geometry (size, shape, roughness) were input to HEC-HMS, which created hydrographs over a time interval for each storm event.

Rainfall and stream gauge data from the U.S. Geological Survey (USGS), the Santa Barbara Coastal Long Term Ecological Research (LTER), and the Santa Barbara County Flood District were utilized. There were five stream gauges on Mission Creek, two of which were used to calibrate the HEC-HMS project (USGS Gauge 11119745 at Rocky Nook Park and USGS Gauge 11119750 at Mission St.) The other three gauges (LTER Gauges on Rattlesnake Creek, Santa Barbara Botanical Gardens and Montecito Street) were used for comparison of modeled to measured discharge.

Precipitation was estimated by assigning weights to precipitation gauges for each sub-basin based on elevation and proximity to the station. Five minute interval rain gauge data from five stations at different elevations in or near the Mission Creek watershed were used (Graham Ranch, KTYD, Stanwood Fire Station, Cater Treatment Plant, and Downtown Santa Barbara).

10.1.1 Runoff Volume

The SCS Curve Number method was used to model runoff volume (discharge as a function of precipitation, named Loss in HEC-HMS) because it allows the modification of curve number to simulate changes in landcover, such as those seen post-fire (SCS 1986). The Curve Number is a parameter representing the runoff potential of the land surface. Higher curve numbers are used for urbanized or areas with low infiltration of precipitation (such as recently burned land), while lower curve numbers represent areas with greater surface permeability and a lesser runoff response. The equation used to model runoff for this model is:

$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$, in which Q is discharge (inches), P is precipitation (inches), I_a is initial abstraction (soil moisture retention in inches), and S is the maximum possible retention (inches) based on the curve number selected.

Curve numbers were estimated using the method described by Santa Barbara County Flood Control (Constantine et. al. 2008). Spatial data for the watersheds was collected from 30 m raster National Land Cover Dataset (U.S. EPA) and SSURGO shape files (Soil Survey Staff) converted to 30 m raster. ArcMap Zonal Statistics was used to determine pre-fire curve numbers for each cell by assigning the intersection of hydrologic soil group with land cover data and calculating the mean for each sub-basin.

10.1.2 Runoff Timing (overland flow and interflow) and Channel Flow (routing)

The Kinematic wave transform (USACE, 1979) was used to describe timing of runoff in sub-basins and channels, as it is appropriate for small, steep, partially urbanized watersheds such as Mission Creek. It represents each sub-watershed as an open channel to which all precipitation not entering the soil flows. It simplifies the routing processes by modeling flow as when gravitational and frictional forces are in equilibrium, an assumption that can be made in steep channels. Flow momentum is described by Manning's equation when these assumptions are made, and movement of a flood wave with this momentum is given by the equation:

$$\frac{\partial A}{\partial t} + \alpha m A^{(m-1)} \frac{\partial A}{\partial x} = q$$

, in which A is the cross-sectional flow area, x is the distance along channel, q is the lateral inflow per unit length of channel, t is time, and m represents surface roughness. The term m, here, is a coefficient equal to 5/3. Alpha (α) is defined by a separate equation:

$$\alpha = \frac{1.486 S^{1/2}}{N}$$

, where S is slope and N is a roughness factor.

10.1.3 HEC-HMS Inputs for Mission Creek

This section provides a map and tables of all parameter inputs used HEC-HMS for Mission Creek watershed. Parameters are listed here for loss (SCS Curve Number method), transform (Kinematic Wave method), and channel routing (Kinematic Wave method).

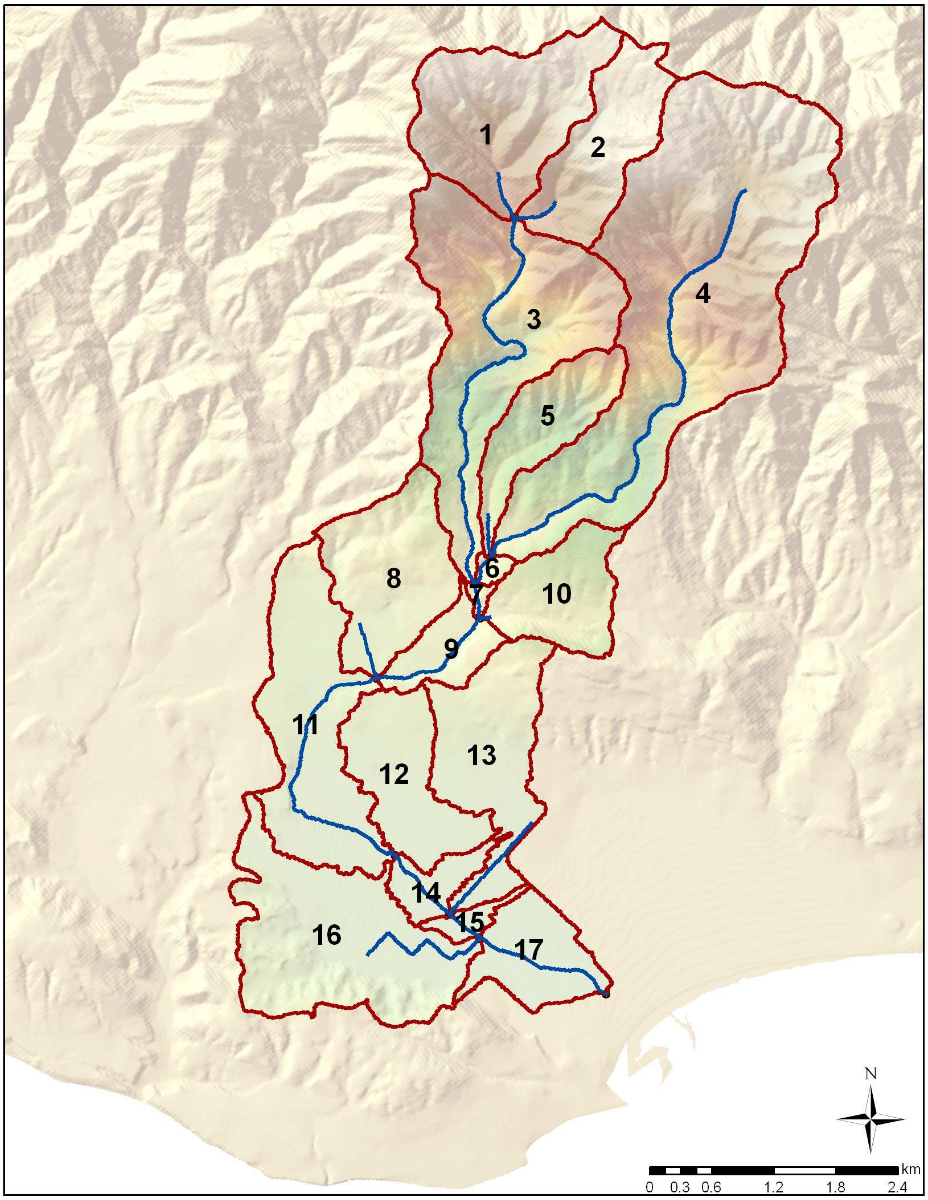


Figure 10.1-A: Sub-basin delineation for Mission Creek Watershed used in HEC-HMS

Table 10.1-A: Mission Creek pre-fire and fire Scenario Curve Numbers under different antecedent moisture conditions

	Prefire				**Medium/High Intensity Fire (Large Fire Scenario)**				**Medium/High Intensity Fire (Small Fire Scenario)**		
Subbasin	*Dry*	*Average*	*Wet*		*Dry*	*Average*	*Wet*		*DRY*	*Average*	*WET*
1	60	80	91		92	95	95		60	80	91
2	61	80	91		92	95	95		91	92	95
3	60	79	90		91	95	95		60	79	90
4	60	79	90		91	95	95		90	91	95
5	59	79	90		92	95	95		59	79	90
6	61	67	81		67	91	81		61	67	81
7	56	76	84		76	84	84		56	76	84
8	65	83	89		83	89	89		65	83	89
9	51	70	80		70	80	80		51	70	80
10	64	83	90		83	90	90		64	83	90
11	66	84	88		84	88	88		66	84	88
12	71	89	93		89	93	93		71	89	93
13	72	89	93		89	93	93		72	89	93
14	68	86	89		86	89	89		68	86	89
15	69	87	90		87	90	90		69	87	90
16	60	79	84		79	84	84		60	79	84
17	65	83	86		83	86	86		65	83	86

Table 10.1-B: Basin Plane Kinematic Wave Parameters

	Length	**Slope**	**Roughness**	**% Area**	**RS**
Basin01(Plane 1)	2224.5	0.676	0.24	44	5
Basin01(Plane 2)	2224.5	0.515	0.24	56	5
Basin02(Plane 1)	786.3	0.449	0.24	47	5
Basin02(Plane 2)	786.3	0.495	0.24	53	5
Basin03(Plane 1)	6071.2	0.509	0.24	54	5
Basin03(Plane 2)	6071.2	0.464	0.24	46	5
Basin04(Plane 1)	5051	0.478	0.24	52	5
Basin04(Plane 2)	5051	0.455	0.24	48	5
Basin05(Plane 1)	1584.5	0.444	0.24	50	5
Basin05(Plane 2)	1584.5	0.379	0.24	50	5
Basin06(Plane 1)	391	0.283	0.24	19	5
Basin06(Plane 2)	391	0.303	0.24	81	5
Basin07(Plane 1)	233.5	0.101	0.12	44	5
Basin07(Plane 2)	233.5	0.28	0.16	56	5
Basin08(Plane 1)	918.7	0.147	0.14	56	5
Basin08(Plane 2)	918.7	0.242	0.18	44	5
Basin09(Plane 1)	1896.7	0.229	0.12	37	5
Basin09(Plane 2)	1896.7	0.178	0.09	63	5
Basin10(Plane 1)	1445.7	0.073	0.23	53	5
Basin10(Plane 2)	1445.7	0.19	0.12	47	5
Basin11(Plane 1)	3275.2	0.044	0.03	71	5
Basin11(Plane 2)	3473.5	0.044	0.03	29	5
Basin12(Plane 1)	1082.5	0.039	0.02	54	5
Basin12(Plane 2)	1082.5	0.039	0.02	46	5
Basin13(Plane 1)	2747	0.054	0.02	37	5
Basin13(Plane 2)	2747	0.054	0.02	63	5
Basin14(Plane 1)	1204.4	0.018	0.02	42	5
Basin14(Plane 2)	1204.4	0.031	0.02	58	5
Basin15(Plane 1)	582.4	0.018	0.02	40	5
Basin15(Plane 2)	582.4	0.016	0.02	60	5
Basin16(Plane 1)	3685	0.089	0.02	60	5
Basin16(Plane 2)	3685	0.185	0.02	40	5
Basin17(Plane 1)	1390	0.028	0.02	44	5
Basin17(Plane 2)	1390	0.012	0.02	56	5

Table 10.1-C: Sub-basin Channel Kinematic Wave Parameters

	Length	*Slope*	*RS*	*Shape*	*Roughness*
Basin01	1872.8	0.09	5	Trapezoid	0.06
Basin02	786.3	0.09	5	Trapezoid	0.06
Basin03	5466.45	0.09	5	Trapezoid	0.05
Basin04	3959.25	0.15	5	Trapezoid	0.55
Basin05	1584.5	0.08	5	Trapezoid	0.045
Basin06	391	0.04	5	Trapezoid	0.045
Basin07	233.5	0.09	5	Trapezoid	0.045
Basin08	918.7	0.09	5	Trapezoid	0.04
Basin09	1414.4	0.04	5	Trapezoid	0.04
Basin10	1445.7	0.03	5	Trapezoid	0.04
Basin11	3374.35	0.01	5	Trapezoid	0.035
Basin12	948.4	0.02	5	Trapezoid	0.035
Basin13	2355.45	0.02	5	Trapezoid	0.035
Basin14	921.25	0.01	5	Trapezoid	0.035
Basin15	582.4	0.01	5	Trapezoid	0.03
Basin16	3057.45	0.01	5	Trapezoid	0.03
Basin17	1390	0.01	5	Trapezoid	0.03

10.1.4 Additional Results

Table 10.1-D: HEC-HMS peak discharge predictions for various storms, fire scenarios, and antecedent moisture conditions at two gauges in the Mission Creek watershed.

			Mission Street (USGS 11112750)	Montecito Street (LTER)
Storm	Fire Scenario	Antecedent Moisture	Peak Discharge (cfs)	Peak Discharge (cfs)
2 year	No Fire	Dry	841	1014
	Small Fire	Dry	2144	2264
	Large Fire	Dry	3362	3500
	Large Fire	Wet	4217	4789
5 year	No Fire	Dry	2027	2377
	Small Fire	Dry	3924	4221
	Large Fire	Dry	4793	6351
	Large Fire	Wet	6785	7732
10 year	No Fire	Dry	2653	2236
	Small Fire	Dry	4860	5397
	Large Fire	Dry	5803	6351
	Large Fire	Wet	8127	9127
25 year	No Fire	Dry	4376	5111
	Small Fire	Dry	6778	7640
	Large Fire	Dry	9395	9897
	Large Fire	Wet	10808	12125
50 year	No Fire	Dry	5266	6199
	Small Fire	Dry	9596	10409
	Large Fire	Dry	10794	11578
	Large Fire	Wet	12249	13948
100 year	No Fire	Dry	6598	7806
	Small Fire	Dry	11412	12443
	Large Fire	Dry	12581	13637
	Large Fire	Wet	14040	16046
Jan 7-11, 2005	No Fire (Observed)	Dry	2300	2807
	No Fire (Simulated)	Dry	2801	3348
	Small Fire	Dry	3500	4274
	Large Fire	Dry	3981	4274
	Large Fire	Wet	4136	4765

10.1.4 Log Pearson Type III Analysis

Table 10.1-E: Comparison of HEC-HMS pre-fire predictions to Log Pearson Type III analysis of 36 years of historical runoff records at Mission St. (USGS 11119750) Gauging Station.
Note: The highest recorded reading at this gauge (3090 cfs in 1995) is expected to be a significant underestimation as the flow broke out of the channel above the gauging station during this event.

Recurrence Interval (years)	Log Pearson Type III Predictions (cfs)	HEC-HMS Model Predictions (cfs)
2	474	841
5	1139	2027
10	1874	2653
25	3279	4376
50	4788	5266
100	6807	6598

10.1.5 Sediment Transport Capacity Estimates

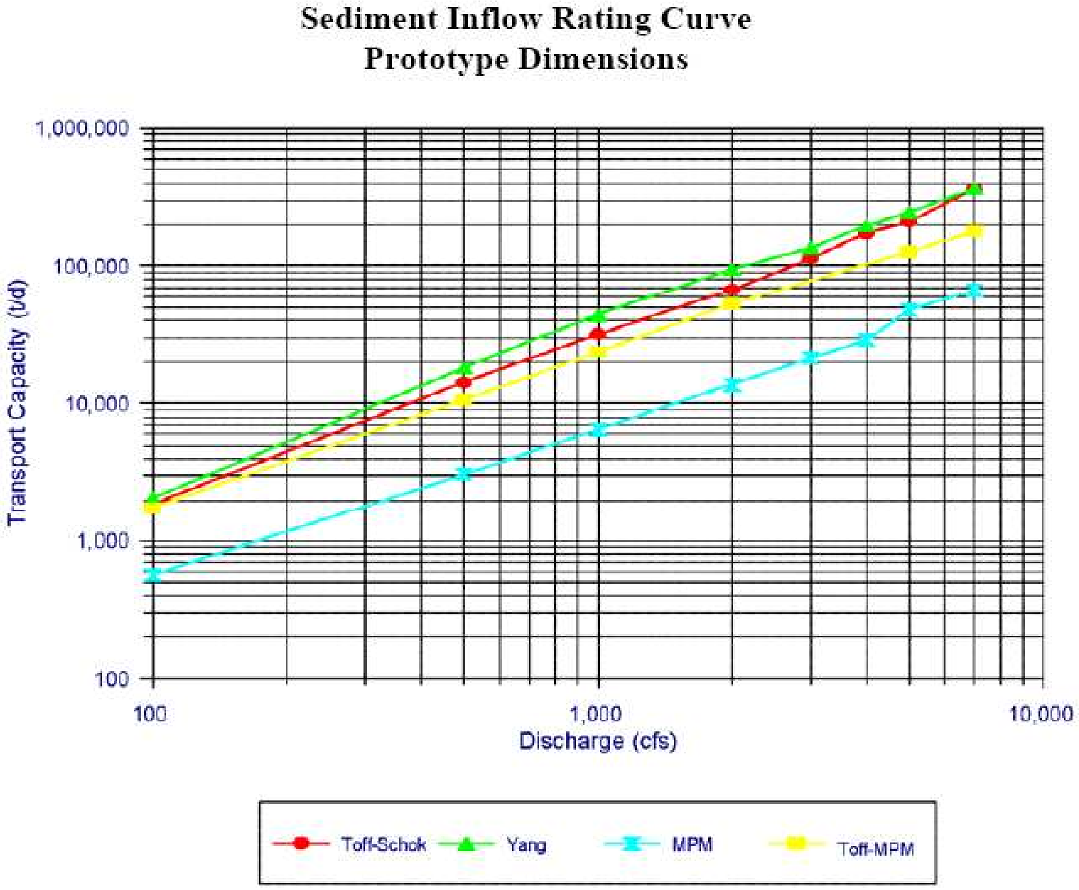


Figure 10.1-B: Estimated sediment transport capacity of Mission Creek near De la Guerra Street from the U.S. Army Corps of Engineers. The blue line represents gravel transport capacity in tons per day, based on the Meyer-Peter-Muller equation. The yellow line represents sand transport capacity in tons per day, based on the Meyer-Peter-Muller equation. The yellow line represents sand transport capacity (tons/day) estimated by Toffaleti's equation. The other rating curves were not used in this project.

APPENDIX 10.2: ERMIT

10.2.1 ERMiT Parameters

Climate Data

ERMiT is linked to PRISM (Parameter-elevation Regressions on Independent Slopes Model) which supplies long-term, spatially-explicit climate data. PRISM is a database of climate files for over 2600 weather stations across the United States. Using this data, it is possible to create a “custom climate” for each watershed, based on geographic coordinates and elevation. A PRISM climate file contains daily precipitation amount and duration, time-to-peak and peak intensity of rainfall. It also contains data on dewpoint temperatures, solar radiation and wind velocity and direction (Robichaud 2007). For details on custom climate files created for San Pedro and Mission Creek watersheds, please see Appendix 10.2.5.

Soil Texture

Soil texture can be described as clay loam, silt loam, sandy loam and loam. We used National Resource Conservation Service (NRCS) soil data from the Soil Survey Geographic Database (SSURGO) to estimate the soil texture in the upper portion of the watershed. We chose to categorize only the upper watershed in ERMiT to get a more accurate idea of what soils might have high erodibility during a rain event. WEPP categorizes soil characteristics into 24 separate parameters. ERMiT has grouped these 24 parameters into four simplified groups in order to facilitate rapid and simple use for managers (Alberts 1995). Our research shows that the dominant soil type within San Pedro and Mission watersheds is silt loam.

Rock Content

ERMiT uses rock content as a parameter which manipulates hydraulic conductivity. Water flows around and through rocks, decreasing the hydraulic conductivity. ERMiT allows a rock content percentage of up to 50%. As rock content increases, erosion also increases. The BAER Team uses visual observations to estimate rock content in San Pedro as 40%. We used the same method to estimate rock content within upper Mission Creek watershed as 50%.

Hillslope Gradient and Horizontal Length

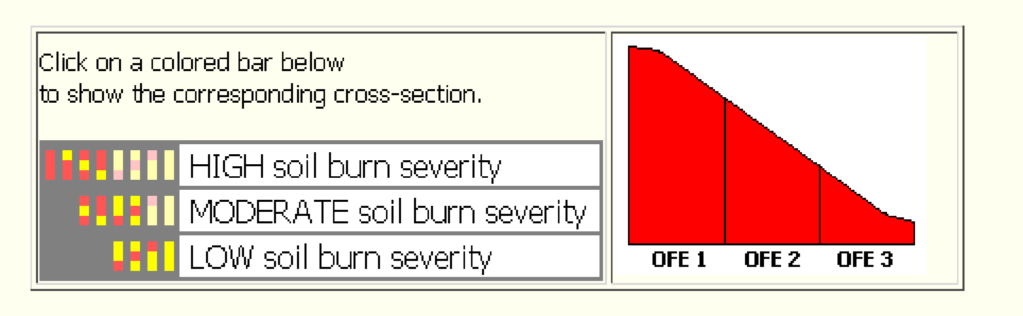
ERMiT requires hillslope gradient measured as a percentage, or change in y/change in x. For example, a 100% slope is equivalent to a 45 degree angle. Additionally, ERMiT allows the separation of the hillslope into top, middle and toe, in order to better visualize the dynamics of overland flow. Lastly, ERMiT requires a horizontal hillslope length measured in feet. The maximum allowable hillslope horizontal length is 300 meters (1000 ft). We estimated these parameters through zonal statistical analyses of the Digital Elevation Models of each watershed.

Soil Burn Severity Class

The user may designate high, medium or low soil burn severity. ERMiT calls any section of the watershed with similar soil, vegetation and slope an Overland Flow Element (OFE). The model allows three OFEs for each watershed and, based on the categorization of the soil burn severity, models various spatial combinations of burn severity. There are 8 possible burn scenarios for high burn intensity, 6 for a medium burn and 4 for a low burn intensity (see graphic below)

.

Fire Burn Severity Overland Flow Elements



Click on a colored bar below
to show the corresponding cross-section.

Pre-fire Community

ERMiT allows three options for vegetation type—forest, rangeland or chaparral. For our purposes, we worked only within the chaparrallian vegetation type. The parameter pre-fire community requires the entry of % cover shrub, grass and bare lands within the watershed. We chose to categorize developed land as "bare" and agricultural land as "grass".

10.2.2 Sensitivity Analysis

The two factors which effect sediment delivery the strongest are soil texture and fire intensity. Clay loam yields the highest sediment delivery, while sandy loam produces roughly half of the sediment of clay loam, all other parameters being held steady. Likewise, fire intensity can double the sediment delivery probability for any give hillslope.

The model is least sensitive to percent land cover, as this parameter has almost no effect on the model output. Although none of the combinations varied by more than 1 ton/acre, combinations with larger areas of bare hillslope resulted in slightly higher sediment yields.

As expected, the sediment delivery probability increases as horizontal hillslope length increases. All other parameters fixed, the sediment delivery exceedance probability increases roughly 1 ton/acre with each 100 ft. increase of the horizontal hillslope length.

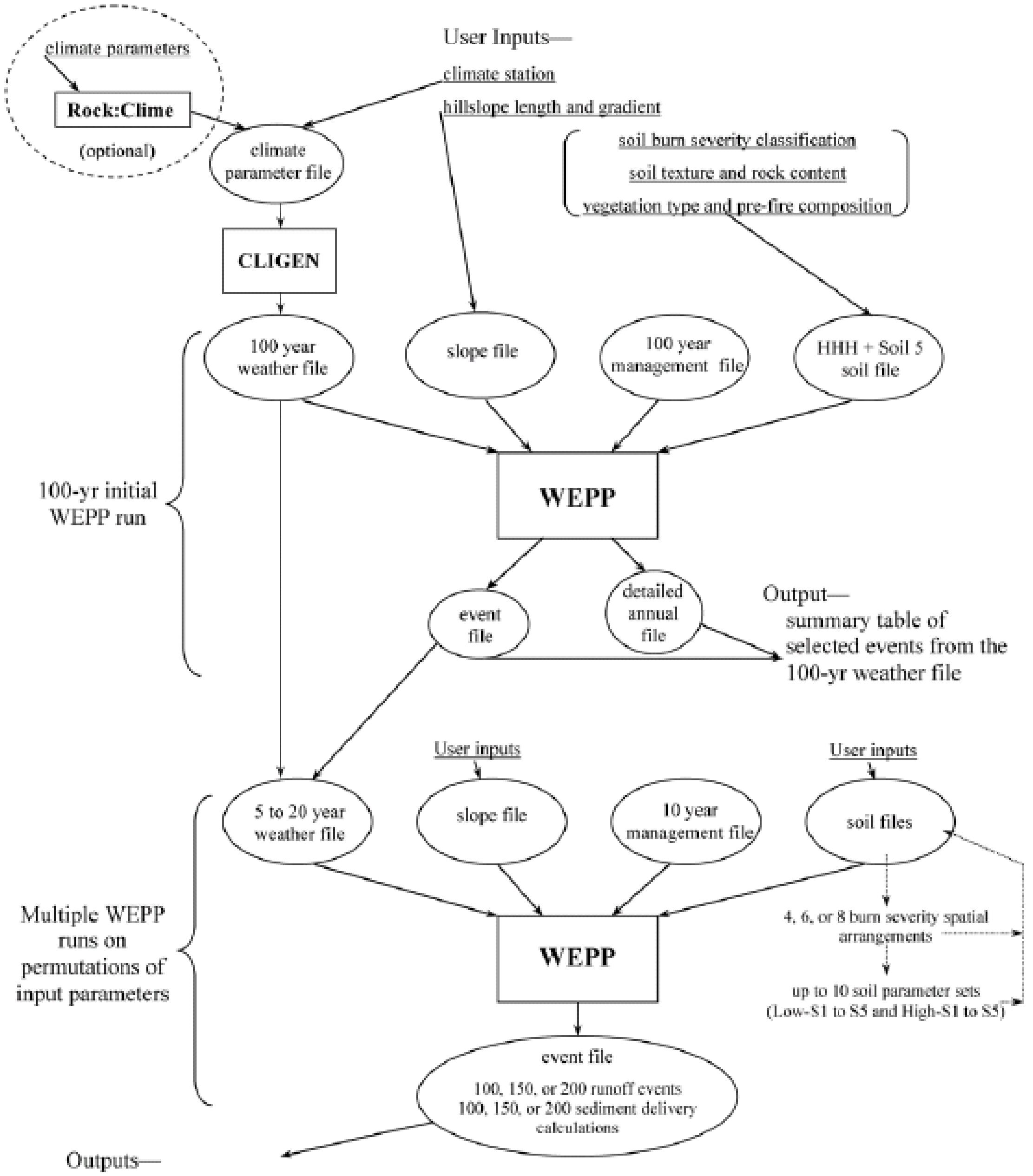
10.2.3 WEPP Flow Diagram

WEPP is described as a "…process-based erosion model used with a process based hydrology model, a daily water balance model, a plan growth and residue decomposition model, a climate generator and a soil consolidation model…" which combine to create a sophisticated modeling tool (Flanagan and Livingston 1995). The synthesis of several steady-state continuity equations which mimic multiple co-occurring dynamic processes has advantages over static empirical models such as Rowe et al (1949). WEPP allows the estimation of soil loss both temporally and spatially, as well as enables the user to extrapolate findings to large-scale watersheds (Nearing et al 1989).

ERMiT is a simplified user interface which runs WEPP based on common post-fire soil and hillslope characteristics. WEPP uses historical climate data from nearby weather stations to create a 100 yr event-based climate history. ERMiT takes the user input and transforms it into "sets" of parameters to create a "slope file" and "soil file."

ERMiT runs WEPP for "most erodible" soil parameters (these WEPP parameters were taken from a range of field measurements and broken into 5 categories of occurrence probability, from "most erodible" to "least erodible") in conjunction with a 100-year runoff event. The model also runs for the 75th, 50th 20th, 10th, 5th, and annual runoff event. The three parameters requiring variation: weather, soil burn severity and soil characteristics, are given independent occurrence probabilities, which are then combined to determine the probability of each of the 100, 150 or 200 predictions produced by the WEPP application.

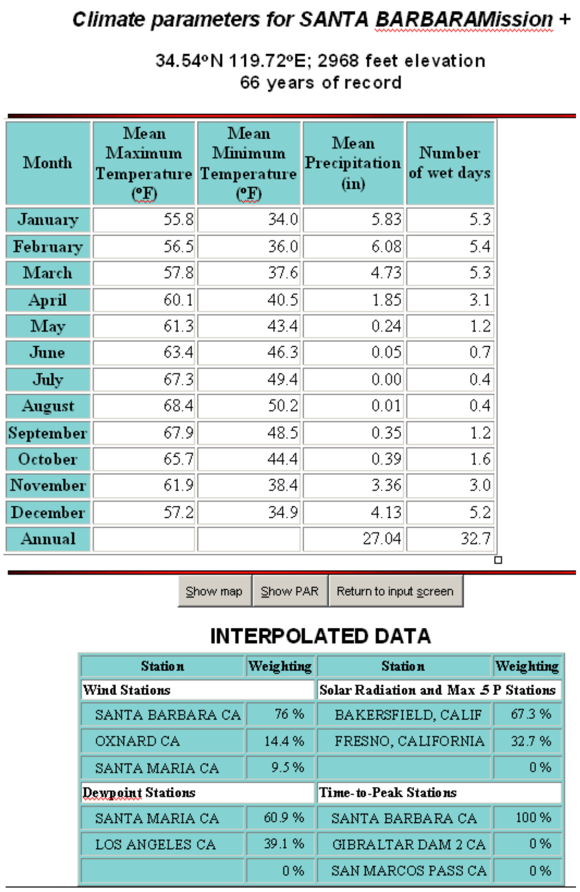
A process-based flow diagram detailing the WEPP inputs and outputs is shown on the next page.


climate parameters
Rock:Clime
(optional)
User Inputs—
climate station
hillslope length and gradient
climate parameter file
soil burn severity classification
soil texture and rock content
vegetation type and pre-fire composition
CLIGEN
100 year weather file
slope file
100 year management file
HHH + Soil 5 soil file
100-yr initial WEPP run
WEPP
event file
detailed annual file
Output—
summary table of selected events from the 100-yr weather file
User inputs
User inputs
5 to 20 year weather file
slope file
10 year management file
soil files
Multiple WEPP runs on permutations of input parameters
4, 6, or 8 burn severity spatial arrangements
WEPP
up to 10 soil parameter sets (Low-S1 to S5 and High-S1 to S5)
event file
100, 150, or 200 runoff events
100, 150, or 200 sediment delivery calculations
Outputs—

10.2.4 Summary of Sedimentation Estimates from Literature

	Sediment Delivery (tons/acre)
NO FIRE (Rowe et al 1954)	***3.9***
Published Literature	
Painted Cave Fire (Keller 1997) (total area)	***12.8***
Painted Cave Fire (Keller 1997) (burned area)	***53.9***
CA Chaparral (Wells 1981)	***13***
CA Chaparral (Krammes 1960)	***25***
San Bdo Forest-Panorama Fire (mixed treatments) (Tyrrel 1981)	***47-88***
Mission Creek watershed w/fire, all events	
Rowe et al (1954)	***124.1***

10.2.5 Custom Climates: Historical PRISM climate files



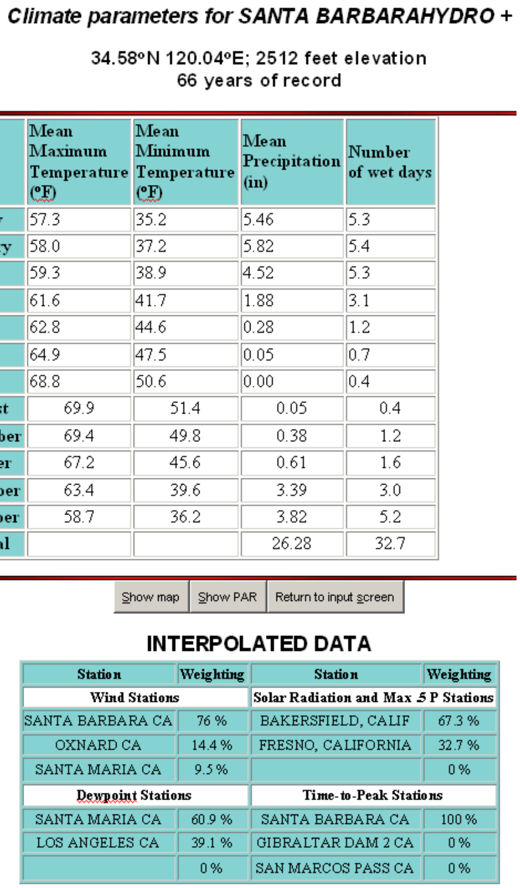
Climate parameters for SANTA BARBARAMission +

34.54ºN 119.72ºE; 2968 feet elevation
66 years of record

Month	Mean Maximum Temperature (ºF)	Mean Minimum Temperature (ºF)	Mean Precipitation (in)	Number of wet days
January	55.8	34.0	5.83	5.3
February	56.5	36.0	6.08	5.4
March	57.8	37.6	4.73	5.3
April	60.1	40.5	1.85	3.1
May	61.3	43.4	0.24	1.2
June	63.4	46.3	0.05	0.7
July	67.3	49.4	0.00	0.4
August	68.4	50.2	0.01	0.4
September	67.9	48.5	0.35	1.2
October	65.7	44.4	0.39	1.6
November	61.9	38.4	3.36	3.0
December	57.2	34.9	4.13	5.2
Annual			27.04	32.7

INTERPOLATED DATA

Station	Weighting	Station	Weighting
Wind Stations		**Solar Radiation and Max .5 P Stations**	
SANTA BARBARA CA	76 %	BAKERSFIELD, CALIF	67.3 %
OXNARD CA	14.4 %	FRESNO, CALIFORNIA	32.7 %
SANTA MARIA CA	9.5 %		0 %
Dewpoint Stations		**Time-to-Peak Stations**	
SANTA MARIA CA	60.9 %	SANTA BARBARA CA	100 %
LOS ANGELES CA	39.1 %	GIBRALTAR DAM 2 CA	0 %
	0 %	SAN MARCOS PASS CA	0 %



Climate parameters for SANTA BARBARAHYDRO +

34.58°N 120.04°E; 2512 feet elevation
66 years of record

Month	Mean Maximum Temperature (°F)	Mean Minimum Temperature (°F)	Mean Precipitation (in)	Number of wet days
January	57.3	35.2	5.46	5.3
February	58.0	37.2	5.82	5.4
March	59.3	38.9	4.52	5.3
April	61.6	41.7	1.88	3.1
May	62.8	44.6	0.28	1.2
June	64.9	47.5	0.05	0.7
July	68.8	50.6	0.00	0.4
August	69.9	51.4	0.05	0.4
September	69.4	49.8	0.38	1.2
October	67.2	45.6	0.61	1.6
November	63.4	39.6	3.39	3.0
December	58.7	36.2	3.82	5.2
Annual			26.28	32.7

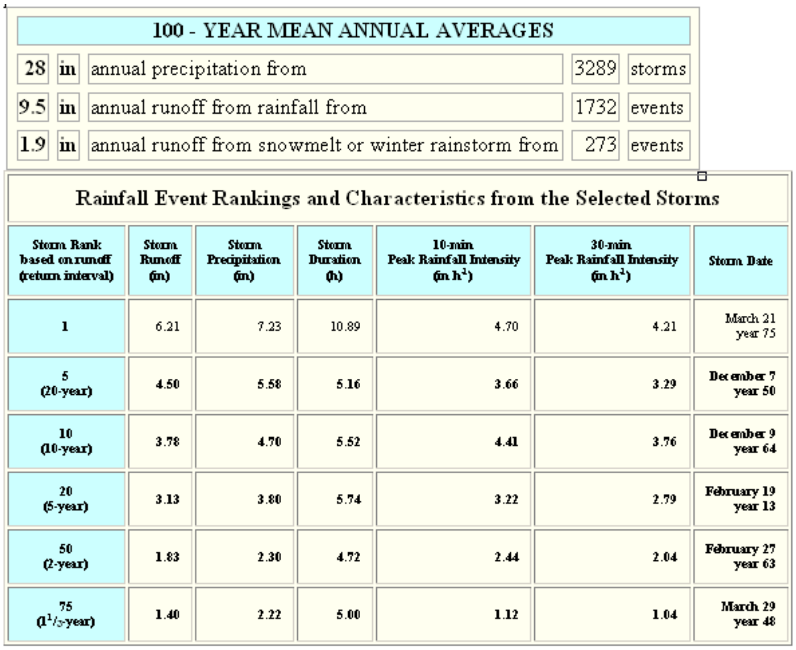
INTERPOLATED DATA

Station	Weighting	Station	Weighting
Wind Stations		**Solar Radiation and Max .5 P Stations**	
SANTA BARBARA CA	76 %	BAKERSFIELD, CALIF	67.3 %
OXNARD CA	14.4 %	FRESNO, CALIFORNIA	32.7 %
SANTA MARIA CA	9.5 %		0 %
Dewpoint Stations		**Time-to-Peak Stations**	
SANTA MARIA CA	60.9 %	SANTA BARBARA CA	100 %
LOS ANGELES CA	39.1 %	GIBRALTAR DAM 2 CA	0 %
	0 %	SAN MARCOS PASS CA	0 %

San Pedro Creek Watershed

10.2.5 Custom Climates (continued): 100-yr PRISM including orographic effect

Mission Creek Watershed



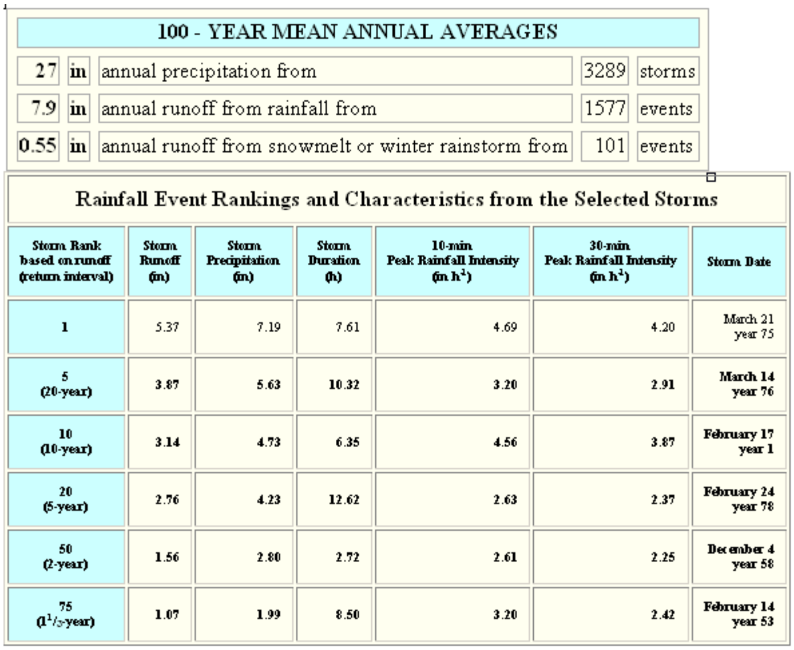
100 - YEAR MEAN ANNUAL AVERAGES

28	in	annual precipitation from	3289	storms
9.5	in	annual runoff from rainfall from	1732	events
1.9	in	annual runoff from snowmelt or winter rainstorm from	273	events

Rainfall Event Rankings and Characteristics from the Selected Storms

Storm Rank based on runoff (return interval)	Storm Runoff (in)	Storm Precipitation (in)	Storm Duration (h)	10-min Peak Rainfall Intensity (in h^{-1})	30-min Peak Rainfall Intensity (in h^{-1})	Storm Date
1	6.21	7.23	10.89	4.70	4.21	March 21 year 75
5 (20-year)	4.50	5.58	5.16	3.66	3.29	December 7 year 50
10 (10-year)	3.78	4.70	5.52	4.41	3.76	December 9 year 64
20 (5-year)	3.13	3.80	5.74	3.22	2.79	February 19 year 13
50 (2-year)	1.83	2.30	4.72	2.44	2.04	February 27 year 63
75 (1$^{1}/_{3}$-year)	1.40	2.22	5.00	1.12	1.04	March 29 year 48

San Pedro Watershed



100 - YEAR MEAN ANNUAL AVERAGES

27	in	annual precipitation from	3289	storms
7.9	in	annual runoff from rainfall from	1577	events
0.55	in	annual runoff from snowmelt or winter rainstorm from	101	events

Rainfall Event Rankings and Characteristics from the Selected Storms

Storm Rank based on runoff (return interval)	Storm Runoff (in)	Storm Precipitation (in)	Storm Duration (h)	10-min Peak Rainfall Intensity (in h^{-1})	30-min Peak Rainfall Intensity (in h^{-1})	Storm Date
1	5.37	7.19	7.61	4.69	4.20	March 21 year 75
5 (20-year)	3.87	5.63	10.32	3.20	2.91	March 14 year 76
10 (10-year)	3.14	4.73	6.35	4.56	3.87	February 17 year 1
20 (5-year)	2.76	4.23	12.62	2.63	2.37	February 24 year 78
50 (2-year)	1.56	2.80	2.72	2.61	2.25	December 4 year 58
75 (1$^{1}/_{3}$-year)	1.07	1.99	8.50	3.20	2.42	February 14 year 53

APPENDIX 10.3: SHALSTAB

Inputs

For each lower order reach of each watershed the contribution width and area was required. This information was gathered from Digital Elevation Maps (DEMs) in the ArcMap 3.2 Geographic Information System (GIS). The DEMs for Mission and San Pedro watersheds depict steep mountainous terrain with generally high relief in the upper and middle watershed, leading to foothills and then a gently sloping coastal plain. Topography plays an important role in landslide risk, so calculating areas of convergence between steep slopes from elevation (DEM) data is an important capability of SHALSTAB.

Friction angle

Related to the slope is the friction angle, which depends upon the roughness of surfaces and the shear strength of the soil. In other words, friction angle is the highest angle that can be maintained without collapsing, so a lower angle means less resistance. The default value, 35^o, seems appropriate based on expert suggestion using maps of the raw SSURGO (Soil Survey Geographic) data, and geologic rock types of the region. The model is very sensitive to large changes in this parameter, so it was held constant throughout our analysis.

Soil parameters

The SHALSTAB model uses information from the United States Geological Survey (USGS) SSURGO database. Values for soil depth and bulk density are available for a number of sites throughout both watersheds, but vary greatly between upper and lower watershed. Since the model assesses the entire watershed at once, these parameters could be estimated by averaging over the upper and lower elevations from USGS data. Alternatively, we chose to run the SHALSTAB model with a variety of the most common values in the mid-upper watersheds, since this is the only area seemingly affected by landslides. Furthermore, soils data in the upper watersheds is coarser than in the developed, low-relief regions of Santa Barbara and Goleta.

Soil thickness (depth) is typically deepest in convergent hillslopes where soil accumulates through biogenic soil creep, contributing to hillslope failure and landslides in such regions. Depth was reported in the mid-upper watersheds as 0.25 m, 0.875 m, and 1.5 m, so each of these values was tested for model response and effect on instability. Soil bulk density combines with the volume of soil (from depth values) and the force of gravity to create a weight component, which SHALSTAB can use to compute the soil stability for one unit area of slope. Density does not change much within either watershed, and most estimates for this area average around 1450 kg/cm^3, therefore we did not alter this value in our analysis (Soil Survey Staff).

Shallow colluvium is much more stable than deep soils. High soil thickness is found in areas where topography drives convergent downslope movement of soil. In these areas, water is also forced to accumulate, raising the water table and water pressures, lowering the q/T ratio, and increasing the risk for landslides.

Soil cohesion

Soil has cohesive properties in particles that naturally stick together, such as clays and organic matter. Furthermore, vegetative roots bind particles to one another, the substrate, and stable soil, creating an important anchoring function on potentially instable slopes. Plants play other important roles in stabilizing soil, as the canopy intercepts intense rainfall, promotes evapotranspiration and removes moisture, lowering the soil water pressure. Since vegetation is removed during wildfires, soil cohesion was a very important parameter to investigate in our analysis.

Unfortunately, field measurements of cohesion were not available for the Mission Creek or San Pedro Watersheds for this project. SHALSTAB provides a default cohesion value of 2000 n/m^2. However, this program was designed in Oregon, where tree and root systems are much more prolific, and rainfall significantly greater than in southern California. Therefore, the cohesion of Santa Barbara is likely much lower (1000 n/m^2), and significantly lower under fire conditions. We chose cohesion of 500 n/m^2 to represent a medium intensity fire, and lowered the cohesion to 0 n/m^2 for a high intensity fire scenario. This same adjustment to cohesion was made by SHALSTAB creators to model runoff and erosion effects in the Oakland firestorm area (Dietrich & Booker 1995).