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Post-Fire Debris Flows: Leveraging Science for Environmental Management and Community Resiliency

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Bren School of Environmental Science & Management by

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As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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

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The University campus and study watersheds are located on Indigenous land. In recognizing the traditional custodians of the land, we share this acknowledgement to educate and pay respect for the Chumash people, the history and culture of the community, and all America's First Peoples. We pay respect to the Chumash Elders past, present and future for they hold the memories, traditions, and culture of this area, which is a place of learning for people from all over the world.

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Abstract

The movement of soil particles and rocks down hillslopes has affected the southern Santa Barbara County foothills over millions of years. The landscape has been shaped by the periodic cascades of soil debris in Santa Barbara County watersheds. Sediment transport from higher elevations to lower elevations, driven by gravity, can be exacerbated by soil cohesion, rainfall intensity, wildfire, and topographical relief. The combination of these factors influences the overall volume of sediment transported. Predicting the volume of a debris flow often has large uncertainty. Debris flows can have dire consequences, as evidenced by the post-Thomas Fire event on January 9, 2018, where 23 people lost their lives. With the built environment encroaching into potential inundation zones, adaptive management strategies can limit the risk to those most vulnerable. One such strategy is the conversion of existing debris basin infrastructure into slotted outfalls, which better facilitate the transport of fine sediments downstream while also providing improved fish passage for the endangered Southern Steelhead. In addition to infrastructure modifications, beneficial reuse of sediment such as beach nourishment provide further ways to address this issue, particularly considering a changing climate. This project (1) modeled debris flow probabilities and volumes with geospatial tools and datasets, (2) evaluated environmental and socioeconomic impacts of sediment from debris flows via cost-benefit analysis, and (3) examined the broader implications of climate change influence on debris flow recurrence and volumes.

SECTION 1 - Executive Summary

Debris flows in Santa Barbara County are a public management concern, particularly due to threats they pose to people and property. This study focuses on characteristics and impacts of post-fire debris flow in three Montecito-area watersheds. The steep hillslopes of the Montecito Creek, San Ysidro Creek, and Romero Canyon Creek watersheds are prone to varying amounts of sediment transport. In the 1960s and 1970s, the Army Corps of Engineers (ACOE) constructed debris retention basins to mitigate hazard from debris flow to the downstream communities. This infrastructure reduces hazard by capturing large debris moving from higher elevations but presents additional management challenges with socioeconomic and environmental consequences. These challenges require examination and consideration, especially in a changing climate.

This project addresses the inquiry of South Coast Habitat Restoration (SCHR) to analyze management strategies by (1) modeling debris flow probabilities and volumes with geospatial tools and datasets, (2) evaluating environmental and socioeconomic impacts of debris flow and sediment management mainly via cost-benefit analysis, and (3) examining the broader implications of climate change on debris flow recurrence and volumes.

The study examined the present likelihood of debris flow and major debris flow, and also tested a simulated increase in fire severity and an 18 percent increase in regional precipitation intensity. These were tested separately to examine sensitivity of debris flow to individual impacts of climate change. Mean debris flow probability in all watersheds was unchanged with an increase in either fire severity or precipitation intensity, while major debris flow likelihood increased under both climate change scenarios. For an increase in both fire severity and precipitation intensity, the watersheds experienced an increase in major debris flow probability from 0.4 percent to 0.7 percent.

Using an empirical model, this project estimated the potential volumes of debris generated during post-fire debris flow events in the study watersheds. The results of this modeling indicate that single precipitation events with rainfall intensities ranging from 0.866 in/hr to 1.57 in/hr could produce post-fire debris flow volumes from 75,000 yd^3 to 141,000 yd^3 in Montecito basin, 64,000 yd^3 to 120,000 yd^3 in San Ysidro, and 48,000 yd^3 to 92,000 yd^3 in Romero Canyon. These values can be used as a tool to inform future management decisions and evaluate potential socioeconomic and environmental impacts.

Three separate cost-benefit analyses were performed: (1) the implementation of a redesigned debris basin with slotted outfalls, (2) sediment delivered to Goleta Beach to maintain shoreline, and (3) the direct market sale of sediment. The cost-benefit analysis accounts for selected costs associated with sediment transportation from the basin. The study uses 10-year and 100-year timeframes. The cost-benefit analysis found that transportation prices are the leading cost of sediment management. Out of the three management options examined, replacement of boxed outfalls with slotted outfalls maximizes benefits for the county. The slotted outfall design improves fish passage while avoiding the cost of transporting sediment. The management strategies are not mutually exclusive and can be implemented in combination with one another to maximize public wellbeing.

This study dealt with multidisciplinary facets that are the subjects of active research and was further limited due to the complex nature of the topic. As a result, more local research is necessary to improve accuracy. For instance, this study's probability modeling is based on a larger regional data set, which does not capture unique local characteristics of the study watersheds. A possible next step to improve modeling accuracy is to collect and employ more localized data to predict debris flow volumes and likelihood under various climate conditions. Patterns of climate change will influence the variability of rainfall, fire regime, and vegetation cover. Uncertainty can be addressed as local climate change models continue to advance.

The cost-benefit analysis was limited due to the availability of data capturing true economic values of non-market goods and services. Secondary data used in the cost-benefit analysis comes from varied geographical and temporal settings, which results in assumptions that influence the accuracy of the findings. A next step to address these limitations is to assess the valuation of endangered species habitat in the watersheds. Improvement of this data will give a better idea of the public benefit to be gained from the slotted outfall option. For a comprehensive understanding of beach nourishment value, further research should obtain more applicable estimates of beach erosion rates and the present value of beach area. Additional study can more accurately capture the value of non-market goods, informing future decision-making.

Climate change will be an influential factor for sediment management in the future because of the likelihood of shifts in fire regimes and rainfall intensity. While the exact local impacts of climate change remain inconclusive, precipitation extremes are anticipated to increase. Furthermore, climate change is amplifying autumn wildfire probability in California and lengthening the fire season. Increased intensity of rain events in this region, which remains prone to high wildfire recurrence, underlines an increased need to adapt current strategies of managing sediment and mitigating impacts from debris flows.

There are currently plans, either approved or in progress, to install slotted outfall designs through modification on the debris basins within the study watersheds and across the county. Construction is slated to take place between 2022 and 2027. Another improvement to watershed infrastructure is the building of the Randall Road Debris Basin on San Ysidro Creek, which does not feature a dam structure but rather widens the riparian corridor and moves residences out of the hazard zone. The modification of debris basins is a strategy that facilitates environmental benefits while continuing to protect the built environment. While the slotted outfall redesign option is being implemented already, other management strategies discussed in this report can be used concurrently to achieve outcomes that balance public need with environmental benefits.

Debris flow hazard and sediment generation remain constant management concerns in the region, which will continue into the future. While modification of existing infrastructure can help alleviate the accumulation of fine sediments, management that considers the public good of sediment resources (i.e., beneficial reuse) can further accrue societal benefits. Field measurements and modeling will be needed to accurately estimate debris flow recurrence and volume, particularly as climate change influences fire regimes and precipitation intensity. Continued refinement of analytical tools is an important step to understand the potential hazard and sediment management challenges underlying future debris flow events. Using science to reduce uncertainty can give managers a meaningful edge in the challenge of post-fire debris flow in a changing climate.

SECTION 2 - Project Overview

Introduction

Southern California coastal watersheds have a long history of fire and flooding recurrence cycles. This natural process leaves behind burned hillslopes with hydrophobic soils that are more susceptible to mass wasting events like debris flows. Additionally, watersheds in the Southern California transverse ranges are characterized by steep slopes and soils composed of soft, easily fracturable material that can slide effortlessly in a mass wasting event under conducive conditions (Kean et al., 2019).

Debris flows–sometimes referred to as mudslides, mudflows, lahars, or debris avalanches–are a geological phenomenon in which water-laden soil masses and rocks move down mountainsides into stream channels, entrain objects in their paths, and form muddy deposits on valley floors (Iverson, 1997). They are particularly dangerous to life and property because they move quickly, destroy objects in their paths, and often strike without warning (USGS, 2005). Debris flows generally occur during periods of intense rainfall or rapid snowmelt and usually start on hillsides or mountains. Debris flows can travel at speeds up to and exceeding 35 mph and can carry large items such as boulders, trees, and cars (Bugnion et al., 2012). Areas recently burned by fire are especially susceptible to debris flows, including areas downslope and outside of the burned area.

Figure 2.1 - Debris Runout flow across Highway 101. Source: (Wally Skalji)

Many California coastal communities at the base of watersheds in the California transverse ranges are at risk of flash floods and accompanying sediment flows after moderate to heavy precipitation events. Wildfire events exacerbate this effect before rain because of the reduction of vegetation cover and the resulting hydrophobic soil after a fire (Pierson et al., 2001). As the size of the debris flow increases, larger particles are entrained, and channel erosion occurs (Benda & Dunne, 1997). Multiple debris flows may be generated from eroding mountainous portions of the drainage basin. The magnitude of debris flows varies as a function of fire severity, precipitation rate, and sediment supply. Regularly, varying fluxes of sediment enter debris basins, with variation correlated largely with precipitation (Lancaster et al., 2019).

A prime example of a debris flow produced by this fire-flood cycle occurred on January 9th, 2018, in Montecito, CA, a community of southern Santa Barbara County (Figure 2.1). The 2018 Montecito mudslide demonstrated the significant hazard these events pose on communities built within the coastal ranges. The 2017 Thomas Fire, a massive fire affecting Ventura and Santa Barbara Counties, was one of multiple wildfires that ignited in southern California in December of that year. It burned approximately 440 mi^2 before being fully contained on January 12th, 2018. At the time, it was the largest wildfire in modern California history. On January 9th, 2018, 3:30 AM PST, 0.54 inches of rain in 5 minutes was reported in the Montecito area (Oakley et al., 2018). Heavy rain on burned hill slopes above the Montecito community resulted in rapid erosion of sediments that sent mud, boulders, and debris flowing down the watershed (Figure 2.2). Homes downstream were severely damaged or destroyed, and 23 residents lost their lives. Mass wasting of soil and stream channels led to catastrophic damage to the watersheds. While multiple watersheds were affected by the Thomas Fire and subsequent debris flows, the most devastating impacts occurred on Montecito Creek, San Ysidro Creek, and Romero Canyon Creek.

Figure 2.2 - Large boulders, debris, and sediments resulted in major impacts on Jan 9, 2018. Source: (Mike Eliason)

During the 1960s and into the 1970s, the United States Army Corps of Engineers (ACOE) installed debris catchment basin facilities at the base of the foothills in many of these steep coastal range watersheds to prevent flooding and mitigate the impact of debris flow events. The debris basins are still in operation and are managed by Santa Barbara County Flood Control District (SBCFCD). Strategically placed downstream of steeply sloped wildlands, the facilities are located where the longitudinal slope profile of the creek generally eases from the mountains. The debris basins are positioned upstream from much of the built environment on the Santa Barbara coastal plains to provide protection from hazards by catching debris entrenched in a flow before endangerment of human life and destruction of property.

The debris basins are excavated on an as-needed routine maintenance basis, and materials are redistributed to several locations throughout Santa Barbara County as needed. This maintenance performed by SBCFCD occurs either following fires in the upper watershed relative to the basins or when the basins have accumulated sediments in advance of the rainy season. This process presents capital costs to SBCFCD and taxpayers associated with excavation and transport/redistribution of sediment via trucks. Additionally, sediment management decisions are associated with unquantified environmental costs such as greenhouse gas (GHG) emissions from transport, degradation of habitat for federally endangered Southern Steelhead Trout, and depletion of sediments from natural systems that maintain downstream habitat and beaches. These costs and sediment delivery vary significantly between extreme debris flow events and lower magnitude sediment flows produced by less severe fire or rainfall intensity. These differences result in varying levels of annual debris basin maintenance, clearing activities, and fiscal costs.

Estimating the volume of sediment delivery in post-fire events gives managers more insight to better forecast the needs of the watershed and the people within them. Rarer, extreme debris flow events, such as what occurred in Montecito on January 9th, 2018, can cause severe adverse impacts. Rainfall scenarios that do not trigger a massive debris flow still result in sediment delivery. These “smaller” events have the potential to “fill in” the debris basin facilities diminishing their retention capacities and thus rendering the basins less effective for sediment storage in future rainfall events. SBCFCD excavates (Figure 2.3) and re-distributes sediment to offsite locations, usually prior to or following a flow into the debris basin. This activity maintains the maximized retention of debris flow should an extreme event occur.

While it is known that sediment delivery increases post-fire events in watersheds, reliably predicting the amount of sediment delivered has remained challenging for managers and earth scientists alike. Factors that make accurate predictions challenging are precipitation, fire intensity/severity, vegetation cover, sediment supply, and hillslope stability. Since the debris basins serve as a “stopping” point for sediment in the creeks, sediment loads can be loosely quantified based on SBCFCD excavation records from when the facilities are desilted. Utilizing this data, local environmental managers can benefit from understanding sediment delivery with more predictability. Data-backed estimates allow for proactive planning of fiscal budgets, communication with first responders and the public, as well as guidance for management efforts.

Figure 2.3 - Cold Springs Debris Basin excavation. Source: Bill Macfadyen

With climate change effecting coastal California communities, local managers continue to take an active approach, developing plans to mitigate hazard. The riparian corridors below the Santa Ynez mountains remain about as populated as they were prior to the 2018 debris flow, with construction of new infrastructure and the rebuilding of damaged properties continuing to occur. Climate change must be considered and incorporated into sediment management plans to manage continued impacts. Even without considering climate change, there is an estimated 6 percent chance of a high magnitude debris flow event occurring in the next 100 years (Adamaitis, 2020). While predictions of the local impact of climate change remain inconclusive, precipitation extremes are anticipated to increase, and atmospheric river-driven rain events are likely to increase along the West Coast (*Central Coast Region Report*, 2019). Increased intensity of rain events in a region that remains prone to high wildfire recurrence suggests a continued need to manage sediment and mitigate impacts from debris flow.

Purpose and Significance

The January 9th, 2018, Montecito debris flow event resulted in the loss of 23 community members and hundreds of millions of dollars in damage and recovery costs (Kean et al., 2019). This disaster demonstrated the importance of planning and managing the inevitability of high magnitude debris flows. Climate change's effect on the recurrence interval for such large events may be inconclusive; major debris flows like the Montecito event are rare. The likelihood of another event of this scale occurring in the next 100 years is approximately 6 percent (Adamaitis, 2020), partially owing to recovery of vegetation and the reduction of sediment supplies (SBC OEM, 2021). A higher priority from an operational standpoint is SBCFCD's response to smaller events and routine annual maintenance of the watersheds and debris basins. These actions require thoughtful management of watershed sediments. With high environmental, economic, and social implications associated with sediments, ideal solutions are those that are economically feasible and maximize benefits.

Considering debris flow events is essential for preparedness of the community along with county agencies who are responsible for protecting life and property. Other agencies are either tasked with or have a vested interest in protecting local natural resources like the habitats present within the watersheds. Sediment flow events can cause damage to sensitive riparian and forest habitats which may take years to recover (Keeley, 2004). Certain species' populations may be reduced to deficient levels, threatening their recovery with possibilities of local extinction events (Rieman & Clayton, 1997). Transporting sediment and debris from basins to other locations may have deleterious ecological effects on the relocation site due to possible contaminants (Chapman & Anderson, 2005). Sediment debris transportation can also release large GHG emissions via truck transportation. Preventive management strategies and planned infrastructure improvements considered in this project may help reduce artificial sediment flux out of the system, which could have significant conservation effects and mitigate debris flow impacts.

In order to generate a framework for management solutions that address these concerns, a broad community understanding of sediment flow needs to be established for the Montecito-area watersheds. Information about how often flows occur and how much sediment might be generated under various conditions is crucial to this understanding. Through empirical modeling, this project assesses the probability and magnitude of debris flow events in three Montecito-area watersheds: Montecito Creek, San Ysidro Creek, and Romero Creek. All three of these watersheds were heavily impacted by the 2018 post-Thomas fire debris flow event, which resulted in property damage, injury, and death. Even minor to moderate magnitude debris flows have costs and impact management concerns. This analysis produces reasonable metrics to estimate the costs and benefits of various strategies for feasible sediment and debris flow management to improve societal and ecosystem well-being.

The costs of emergency sediment management after the catastrophic January 9th, 2018, event was over $900 million in indirect cost as of January 2020 (Lancaster et al., 2021). The tabulated cost provides a real-world example of how much sediment can cost the public. We complete a limited cost-benefit analysis using an empirical and systematic approach to evaluating management alternatives. The advantage of this method is that it allows for consideration of the many social and environmental consequences of sediment flow events and routine sediment management decisions while also weighing economic costs. It attempts to address stakeholder concerns by examining a multitude of "impact categories" that represent the consequences of actions to relevant stakeholders. We consider many of these factors in our analysis and use proxies where specific data is deficient.

The disadvantage of this approach is that the number of impact categories considered and the granularity of the examination can drastically change the results. Many of the social costs of debris flow and sediment management are difficult to account for in a cost-benefit analysis. For example, urban infrastructure disruptions such as highway integrity and traffic affect the area's workforce and livelihood. However, their quantification depends on many factors that are difficult to assess and have considerable uncertainty. Pollution and contamination release have consequences for the health and safety of nearby urban populations. Assessing the impact requires scientific data that account for complex variables. Due to scope limitations, we examine many of these considerations using a qualitative approach rather than including them in the cost-benefit analysis.

This project aims to address and ameliorate some of the management issues through a comprehensive analysis of the watersheds. Additionally, we address possible hazard mitigation opportunities and methods of increasing the saliency of debris flow events. This can increase levels of safe practices by community residents and decrease the loss of life and property during extreme events.

With intensifying climate change, fires and intense storms are likely to become more common (Oakley et al., 2018). Understanding the future probability of the occurrence of debris flows and sediment fluxes will better enable county and city managers, community members, and the conservation community to make informed decisions with more optimal outcomes. Management strategies can be implemented to mitigate impacts from debris flows and protect human and sensitive ecological communities.

Minor vs. Major Debris Flow Distinction

The distinction between minor and major debris flows is dependent on local settings and damages (Santi et al., 2011). A relatively small magnitude debris flow can incur massive damages to a downhill community, conversely a large magnitude debris flow can occur in uninhabited regions incurring no damage to life or property. Minor debris flows can be expected on a regular basis with or without the presence of fire, while major debris flows have an observed occurrence interval between 10 and 13 years across the wider Southern California region (Kean & Staley, 2021, Cannon et al., 2011), and much longer intervals for a specific location (Keller et al., 2020).

This study considers any debris flow event that does not overflow the debris basins as a minor event. Debris basins fill approximately 25 percent of their holding capacity every 5 to10 years (SBCFCD, 2017). For example, Romero Creek debris basin has a holding capacity of 27,000 yd^3 which implies that over a 5 to 10-year period one can expect small debris flow events to contribute roughly 7,000 yd^3. Inputs are highly dependent on precipitation, with drought periods resulting in multiple years of minimal sediment accumulation. There can be extended periods with minimal sediment accumulation, or rapid aggregation of material which requires management actions.

SBCFCD removes material from basins either in response to fires higher in the watershed or in advance of an incoming rainy season (SBCFCD, 2021). The largest volumes removed from debris basins between 2006 and 2018 were 2,000 yd^3 in 2010 and 2012 respectively, which correlated to a wetter period. 2010 and 2012 were relatively average precipitation years (~20 inches of annual rainfall) while 2011 was well above average (>40 inches) (SBCFCD, 2022). These sediment values are considerably less relative to the volumes of sediment following the major Montecito debris flow event in 2018, though sediment generated by a minor to moderate event still have management implications.

Climate Change-Fire and Precipitation

The 2017 Thomas Fire was the largest fire in recent California history when it was fully extinguished at 281,893 acres and is now the 8th largest wildfire in recent California history (CalFire, 2022). In early December and driven by strong Santa Ana winds through dry vegetation, the fire burned rapidly from Ventura County to the front country of the Santa Ynez Mountains north of Carpinteria and Montecito. Denuding the hillsides in advance of the rainy season, the Thomas Fire created the ideal conditions for a major debris flow with a precipitation event of suitable intensity. Research indicates that climate change may weaken Santa Ana wind conditions in Southern California while increasing seasonality (Guzman-Morales and Gershunov, 2019). Furthermore, climate change is driving an increase in autumn wildfire probability in California (Goss et al., 2020).

Climate change is also driving increased precipitation variability in California. The rainy season is shortening but the probability of intense precipitation increasing (Swain et al., 2018). This would suggest that an increased probability of intense precipitation following extended dry periods, when mixed with shifted fire regimes, would result in an increasing likelihood of minor and major debris flow events (Ren and Lesile, 2020). From both a sediment management and disaster resiliency perspective, it is critical to consider climate change in relation to sediment transport events in the study watersheds, particularly following fire.

Perception of Debris Flow Sediment in the Community

Debris following heavy rainstorms can result in the destruction of property, damage to ecosystems, clogging of drainage conduits, and closure of transportation corridors. When debris exceeds the capacity of the designed infrastructure, risk and uncertainty increase, as does the cost to the community. The threat of high magnitude debris flows is a public cost that flood managers and insurance companies have considered for decades. The costs are well known, but the benefits of sediments are broadly not recognized at a community level. Traditional sediment management can lead to a disparity in the community’s understanding, even going as far as deterring projects that retain sediment in the system. Community understanding of the different sediment management strategies and their associated cost and benefits will need to be addressed for long term solution feasibility.

One lesser-known cost to the community of traditional basin sediment management is the increased risk of stream bank collapse. Hard structures in stream channels like basins or dams retain the sediment, leaving the rest of the stream system starved for material, undercutting streambanks, and lowering streambed elevation over time. The reduced in-stream sediment also impacts trout habitat. This is impactful to trout populations that need pebble-sized substrate to spawn, which is kept out of the system using hard infrastructure (Raleigh et al., 1984). The sediment is also beneficial when used as a beach fill to counteract the effects of erosion. Nourishing beaches increases usability as a public good. If sediment is to be used sustainably on beaches, water quality impacts need to be addressed at a community level (Li et al., 2020).

Project Objectives

The objective of this project is to study the environmental and socioeconomic impacts of sediment from debris flows and other sediment fluxes. We accomplish this by examining the relationship of sediment delivery with fire and intense precipitation events, evaluating sediment management strategies from a cost-benefit perspective, and considering the impact of climate change. Socioeconomic considerations will be determined through the analysis of debris management techniques and studying potential distribution effects. The ancillary objective of this project is to evaluate the risk of debris flows in the future. This will be done by estimating debris flow volumes for current and future climate scenarios. To build a strong foundation for the analysis, our group worked closely with South Coast Habitat Restoration (SCHR) and SBCFCD to understand current practices. The methodology and results from each objective were discussed in separate sections of this report. We developed recommendations for management solutions based upon our analysis, which can be found in the discussion and conclusion sections of the report.

We organized our objectives into the following focus areas:

Objective 1: Modeling debris flow probabilities and volumes with geospatial tools and datasets.

Objective 2: Evaluate environmental, and socioeconomic impacts of sediment from debris flows via cost-benefit analysis.

Objective 3: Examine the broader implications of climate change influence on debris flows recurrence and volume in the study area.

SECTION 3- Background

Geographic Setting

This project's study area centers on three watersheds that were heavily impacted during the January 9th, 2018 debris flow: Montecito Creek, San Ysidro Creek, and Romero Creek. Another watershed, Gobernador Creek, which is in the nearby community of Carpinteria, is used as a reference in this analysis.

The three study watersheds are nestled in the Santa Ynez mountains above the unincorporated community of Montecito, a census-designated place in southeastern Santa Barbara County. Montecito borders the City of Santa Barbara to the east and features primarily suburban residential land use. According to the 2010 census, the population of Montecito was 8,965 residents. Between 2015 and 2019, the median income for Montecito's 3,100 households was $159,706 (2019 dollars). The 2019 median property value in Montecito was $2M, 8.32 times greater than the national average (Census.gov, 2022).

The three watersheds are characterized by steep slopes with sandstone boulder-dominated channels. Due to the transverse orientation of the Santa Ynez Mountains, the creeks flow north-south, draining the steep topography into the coastal plain below. Elevations for the three watersheds range from 0 feet at sea level to 3822 feet at the highest point, with an average slope of 25.6°. Combined, the watersheds encompass roughly 18 mi^2 (Figure 3.1). Individually, the Montecito Creek watershed encompasses 6.6 mi^2 with a mean slope of 24.9°, the San Ysidro Creek watershed encompasses 5.6 mi^2 with a mean slope of 28.5°, and Romero Creek watershed encompasses 5.8 mi^2 with a mean slope of 23.5°. Our reference watershed, Gobernador Creek, has a maximum elevation of 4,680 feet and encompasses 7.2 mi^2 with a mean slope of 33.3°.

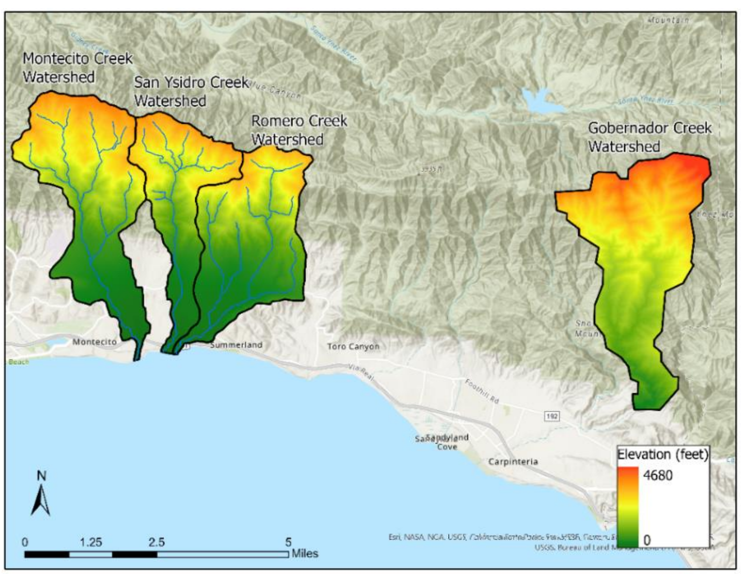

Figure 3.1 - Study watersheds and reference watershed relief.

The watersheds are characterized by natural vegetation higher in the watersheds (which is primarily located within Los Padres National Forest) and residential development in the coastal plain. Much of the development on the coastal plain is built upon prehistoric debris flow runouts, as shown by the presence of boulders ranging in size from six to twenty feet (Keller et al., 2020). Anthropogenic ignitions, development in the wildland urban interface (WUI), and climate change are all influences on shifting the fire regime (Keeley & Syphard, 2016).

A reference watershed used in this analysis is Gobernador Creek, a tributary of Carpinteria Creek, which flows through the City of Carpinteria, a coastal community southeast of Montecito. While suburban development in Montecito abuts the study area creeks with minimal setbacks, Gobernador Creek has larger streamside setbacks. Unlike the Montecito watersheds, land use along Gobernador Creek generally supports agriculture rather than housing. While Gobernador Creek sustained impacts during the January 9th, 2018 debris flow, the impacts were considerably less severe relative to the Montecito area creeks (Lancaster et al., 2021).

In addition to Gobernador Creek, all three of the study watersheds also feature debris basins that were constructed by ACOE following wildfire events (Figure 3.2). The Cold Springs and San Ysidro debris basins were constructed in 1964 following the Coyote Fire, while the Romero and Gobernador basins were built in 1971 after the Romero Fire. All creeks in the study area are federally designated by the National Marine Fisheries Service (NMFS) as critical habitat for the Southern California population of Steelhead Trout. The debris basin on Gobernador Creek was modified in 2008 to promote fish passage while retaining flood control functionality.

In addition to the debris basins installed in the 1960s and 1970s, temporary ringnets have been installed in the study watersheds. Figure 3.2 shows the location of debris basins within the study watersheds, along with ringnet locations which were installed on private property following the January 9th, 2018 debris flow.

Geology

The mountains above Montecito and Santa Barbara consist of steeply dipping Tertiary sedimentary rocks that include thick-bedded durable sandstone, with interbeds of shale, claystone, and silty sandstone (Keaton et al., 2019). These rock types weather to bouldery and cobbly clayey and silty sand sediments (Kean et al., 2019). The region’s drainage basins have large upper sub basins separated from the coastal plain. Montecito is located between narrow steep-sided canyons (Keaton et al., 2019). The area under Montecito and Carpinteria experienced a geologic history that was slightly different from Santa Barbara’s because the shallow Pleistocene epoch seas only extended to what is now presently known as near-shore areas of Montecito and Carpinteria (Hoover, 2020). Terrestrial deposits consisting of cobble, clay, and boulders underlie most of Montecito, forming groundwater basins that provide substantial water supplies to the local community (Hoover, 2020). No rocks in Santa Barbara County are older than the Jurassic period in age (Norris, 2003).

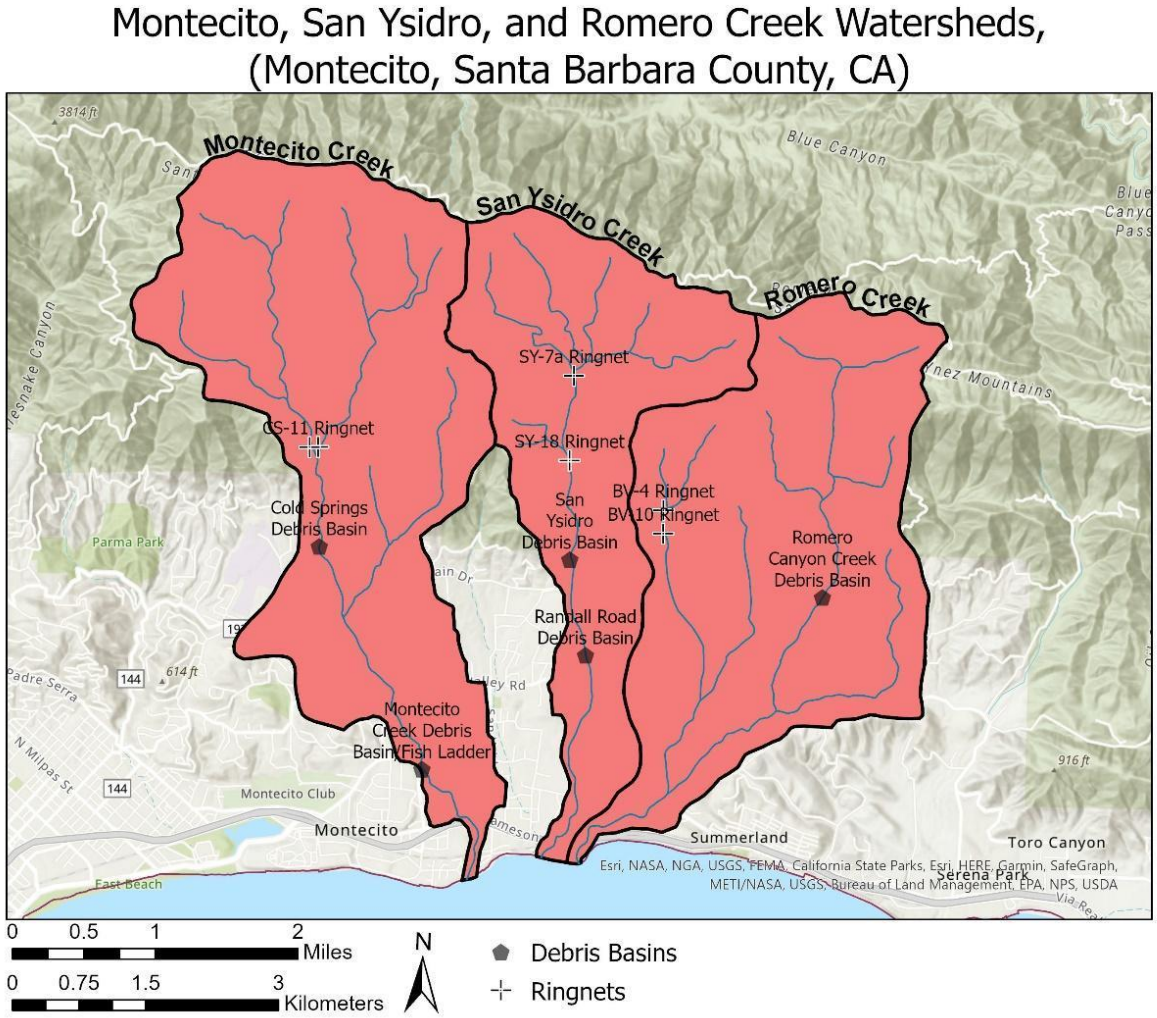

Figure 3.2 - Map of study watersheds with debris basin and ring net locations identified.

Vegetation

The study watersheds are characterized by chaparral vegetation found in Mediterranean climates like California. Two species (Figure 3.3) that can be found in the study watersheds are the manzanita shrub (*Arctostaphylos glauca)* and scrub oak (*Quercus dumosa*) (Baker and Halsey, 2020). Vegetation within the watersheds is also characterized by patches of oak woodland, and riparian buffers along creeks. Chaparral ecosystems are characterized by recurrent disturbance by wildfire, with an average fire return interval ranging from ten to fifty years (Baker and Halsey, 2020). The combustion via wildfire of manzanita and other chaparral species results in hydrophobic soils that increase runoff and sediment transport (Wells, 1987).

Figure 3.3 - Pictures of Manzanita (Arctostaphylos Glauca) and Scrub oak (Quercus Dumosa). Source: (CA Chaparral Institute)

Normalized Difference Vegetation Index (NDVI)

We can monitor plant cover in the watersheds over time using Landsat data. The following images are compiled to show the seasonal variability of vegetation in the watershed. The Normalized Difference Vegetation Index (NDVI) shows the level of healthy plant cover on the land surface. High levels of vegetation are displayed in green and low levels of vegetation in red. The following four maps (Figures 3.4-3.7) illustrate seasonal and conditional variations that influence vegetation cover in the study watersheds.

February of 2016 was part of a drought period that received lower than average precipitation. Vegetation covers the managed lands at the bases of the study watersheds with a notable decrease in cover in the upland portions (Figure 3.4). The irrigation required for developed landscapes results in higher vegetation values when compared to the dryer undeveloped portions. Another factor is the growth pattern of the vegetation in the ecosystem, which is low-lying grass in the winter and accumulates to greater cover over the spring and summer.

August of 2016 shows the cover after the winter and spring growing season as well as a heavy storm in March (Figure 3.5). The summer season historically yields little precipitation, yet the vegetation is still present in the watershed near the end of summer.

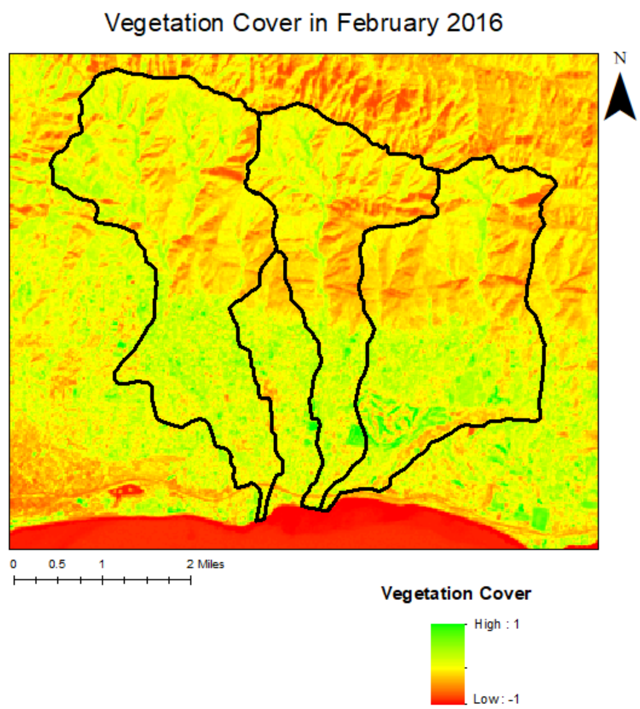

Figure 3.4 - NDVI from February 2016 shows a drought year with lower amounts of vegetation in the watershed.

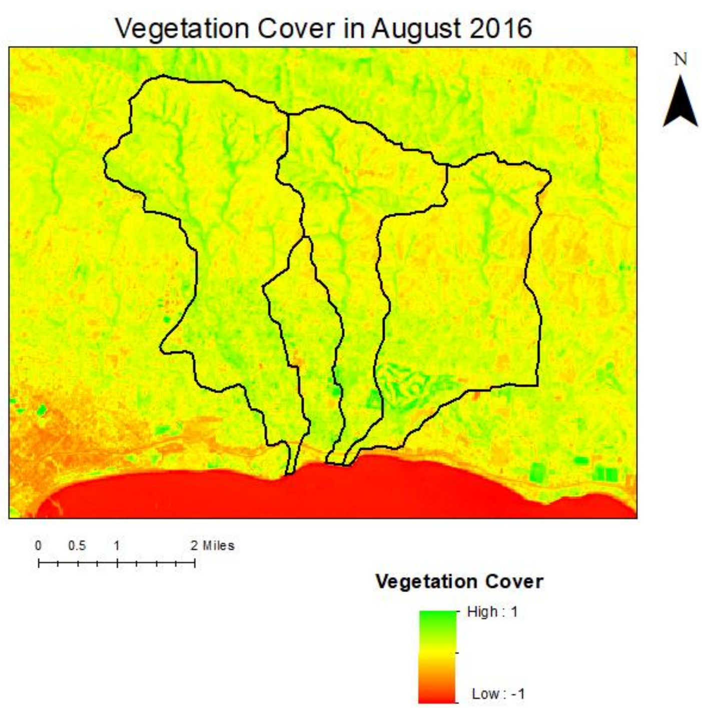

Figure 3.5 - NDVI from August 2016 show an increase in vegetation in the upper watershed then compared to February of the same year.

The NDVI values were much higher in October 2017 due to high precipitation observed in the winter season (Figure 3.5). Fall is a drier season that sees vegetation desiccated.

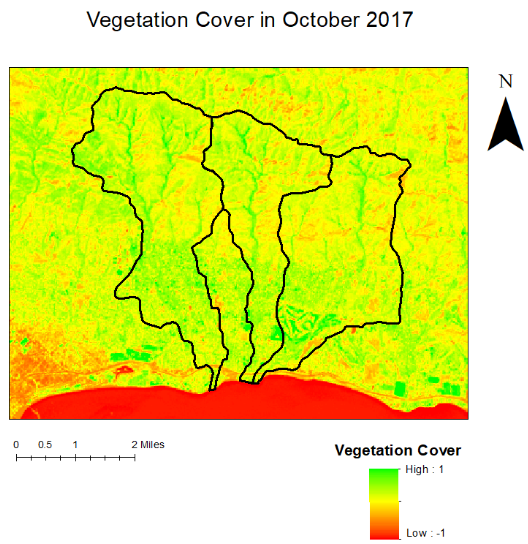

Figure 3.6 - NDVI from October 2017 shows the vegetation cover in the watershed prior to the Thomas Fire.

January shows the starkest difference between seasonal variation and results of wildfire removing the vegetation cover in the upper watersheds (Figure 3.7). Lack of plant is one of the main drivers for debris flows after a rainstorm. The post-Thomas fire rains were less intense than rains observed in March 2016 yet resulted in more sediment transport.

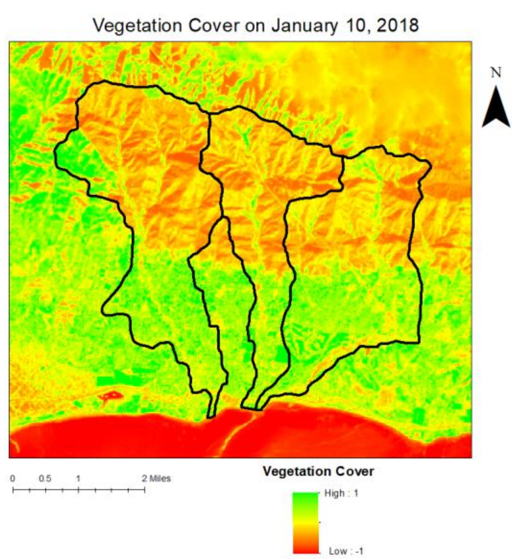

Figure 3.7 - NDVI from January 10th, 2018 shows the rapid transformation of the land surface from October 2017 due to the Thomas Fire and the day after the catastrophic January 9th, 2018 debris flow.

Regional Fire and Debris Flow History

Regional Fire History

Santa Barbara County is characterized by its temperate Mediterranean climate and frequent periods of prolonged drought. Local weather patterns combined with mountain systems dominated by seasonally flammable grasses and chaparral provide conditions that make this region's ecosystem prone to wildfires. There is research indicating that over the past 560 years, large wildfires (greater than 50,000 acres) have occurred in this area on an average of every 20 to 30 years (Mensing et al., 1999).

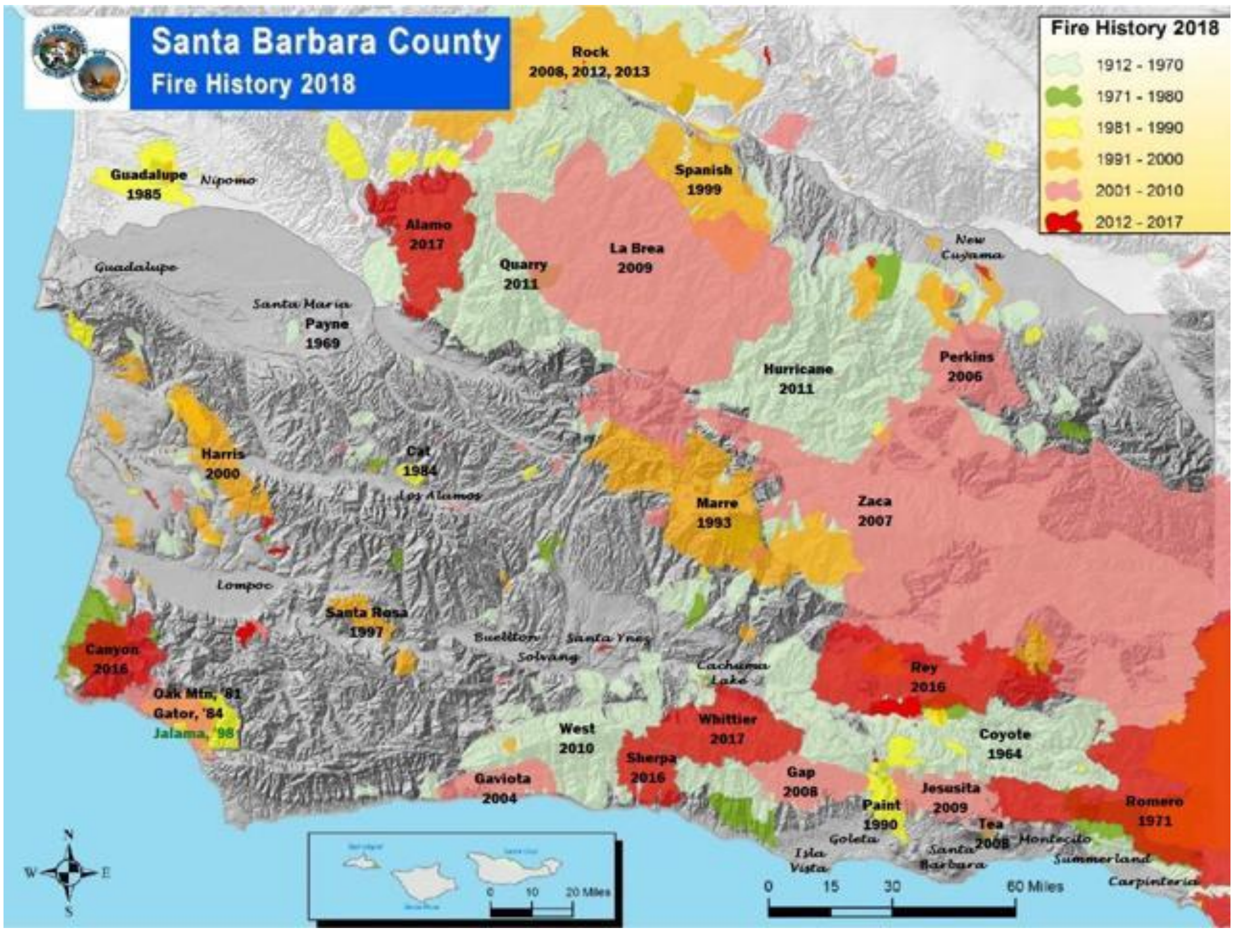

Figure 3.8 - Most major fires in Santa Barbara County, from 1912 to 2017, with their names, approximate size and the year they occurred are shown with burns color-coded by decade. Source: (Santa Barbara Fire Department)

Since the 1950s, the greater Santa Barbara area has averaged one large fire per decade (Figure 3.8); however, the number of large fires within and adjacent to the County has increased substantially over the last decade. Impactful fires and debris flows include the following:

The 1964 Coyote Fire burned east of the San Marcos Pass, consuming 65,339 acres and destroying 106 structures (Figure 3.9). Following the fire, a storm event on November 9th, 1964, caused massive flooding and debris flows in Montecito and San Ysidro Creeks, totaling a damage estimate of $500,000 (ACOE, 1999, Lancaster et al. 2021). Just west, a debris flow destroyed 12 homes and 6 bridges along Mission Creek (Lancaster et al., 2021). Two months later, on January 25th, 1969, a large storm swept over an area above Carpinteria that was previously severely burned in the Coyote Fire, causing debris flows to tributaries of Montecito and Romero Creeks (SBCFCD, 1969). This resulted in flooding over U.S. 101 and an estimated 100 destroyed homes in Montecito, 20 homes and 20 damaged commercial structures in Carpinteria (Lancaster et al., 2021). There are witness reports of 18 to 20-foot-tall walls of debris moving down the inundated channels (ACOE, 1974).

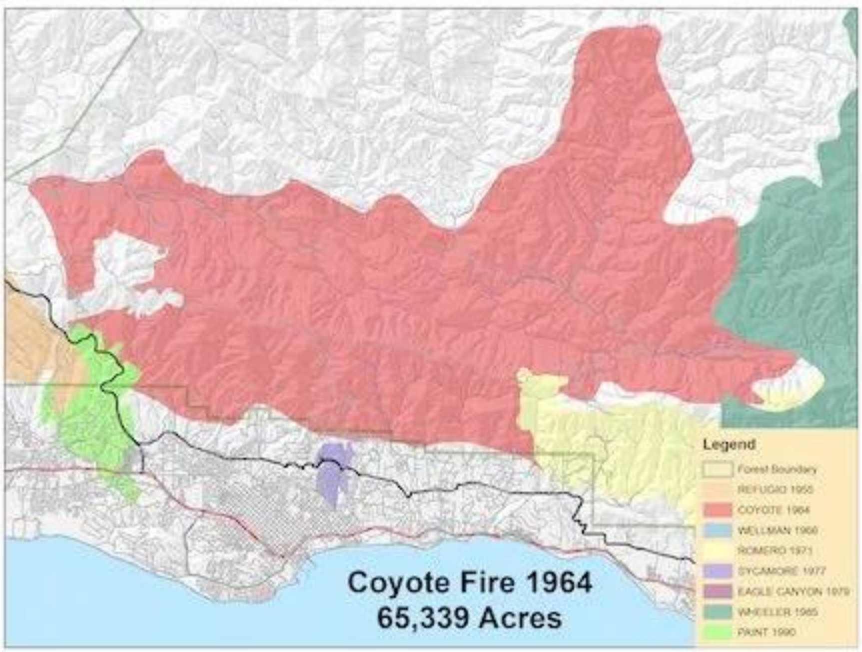

Figure 3.9 - Coyote Fire burn scar. Source: (SB Independent)

The Romero Fire, which began on October 7th, 1971, burned 14,538 acres, took the lives of four firefighters, and destroyed four homes (Hill, 2019). Heavy rains in December brought mud and debris-laden flooding to Romero, Toro Canyon, Santa Monica, and Carpinteria creeks (Lancaster et al., 2021). An estimated 10 to 15 households needed to be evacuated, and U.S. 101 was closed for 8 hours as a 3-foot-tall wall of mud made its way across the highway on its way to the ocean (Figure 3.10) (Lancaster et al., 2021).

Figure 3.10 - View of U.S. 101 overtopped with mud after a debris flow post-Romero Fire. Source: (SB Bucket Brigade)

In 1990 the Painted Cave Fire blazed through Highway 154 and the Painted Cave community. It burnt and eventually made its way across U.S. 101, destroying 500 homes, burning nearly 5,000 acres, and resulting in one lost life before it was contained (Figure 3.11) (Hill, 2019). This was the most destructive fire the Santa Barbara region had seen in decades and spurred statewide collaboration and prompted governments to invest in local solutions to the growing wildfire challenge, including the inception Fire Safe Councils. (Keller et al., 1997).

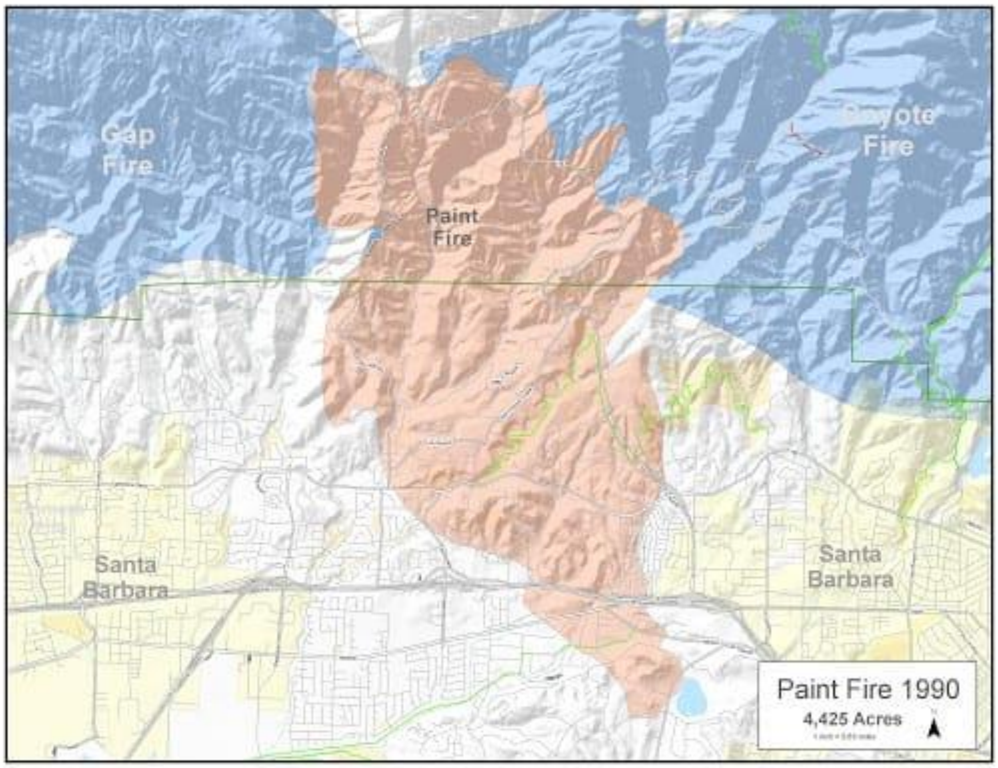

Figure 3.11 - Burn scar of Painted Cave Fire. Source: (SB Bucket Brigade)

A notable three-year stretch of wildfires in the Santa Barbara region began in 2007. The Zaca Fire (2007) burned for four months in the backcountry, spreading over nearly 240,000 acres within its final perimeter, and had a cost of $120 million to contain (CalFire, 2022). 2008 saw the Gap Fire burning 10,000 acres above Goleta and the Tea Fire, which destroyed 210 homes in Montecito, largely attributed to sundowner winds. Sundowner winds are so named because they often begin in the late afternoon or early evening, their onset is typically associated with a rapid rise in temperature and decrease in relative humidity. In the most extreme Sundowner wind events, wind speeds can be of gale force or higher, and temperatures over the coastal plain, and even at the coast itself, can rise significantly above 100°F. These winds have been associated with many of the most destructive fire events that have occurred in the Santa Barbara region (Smith et al., 2018). On May 5th, 2009, the Jesusita Fire started along the Jesusita Trail below Cathedral Peak in the Santa Barbara foothills. The fire spread into the populated areas of Mission and Rattlesnake Canyons, destroying 80 homes and 79 outbuildings while burning 8,733 acres.

In 2016, the 7,400-acre Sherpa Fire started in almost the exact location as the 1955 Refugio Fire and caused the closure of U.S, 101, interrupted Amtrak services and forced the closure of popular state beaches near Gaviota (Hill, 2019). In early 2017, roughly 6 months after the Sherpa Fire, Gaviota experienced an intense rainstorm with a peak 15-minute rainfall intensity rate of .039 in/hr that initiated debris flows and sediment-laden flooding in several watersheds recently burned by the Sherpa Fire (Schwartz et al., 2021). The flows destroyed historic adobes and necessitated the rescue of 12 campers.

Discussed earlier, the 2017 Thomas Fire, a massive fire affecting Ventura and Santa Barbara Counties, was one of multiple wildfires that ignited in southern California in December of that year (Figure 3.12). It burned approximately 281,893 acres (440 mi^2) before being fully contained on January 12th, 2018. At the time, it was the largest wildfire in modern California history. On January 9th, 2018, at 3:30 AM, 0.54 inch of rain in 5 minutes was reported in the Montecito area (Oakley et al., 2018). Shortly thereafter, mud and boulders from the Santa Ynez Mountains flowed down creeks and valleys into Montecito (Cui et al., 2018). These post-fire debris flows consisting of mud, boulders, and tree branches that were up to 15 feet in height, moving debris including boulders up to 20 feet at estimated speeds of up to 20 miles per hour into the lower areas of Montecito. This resulted in 23 deaths and over 150 hospitalizations. The disaster caused at least \$177 million in property damage, at least \$7 million in emergency responses, and another \$43 million in cleaning costs (Kean et al., 2019).

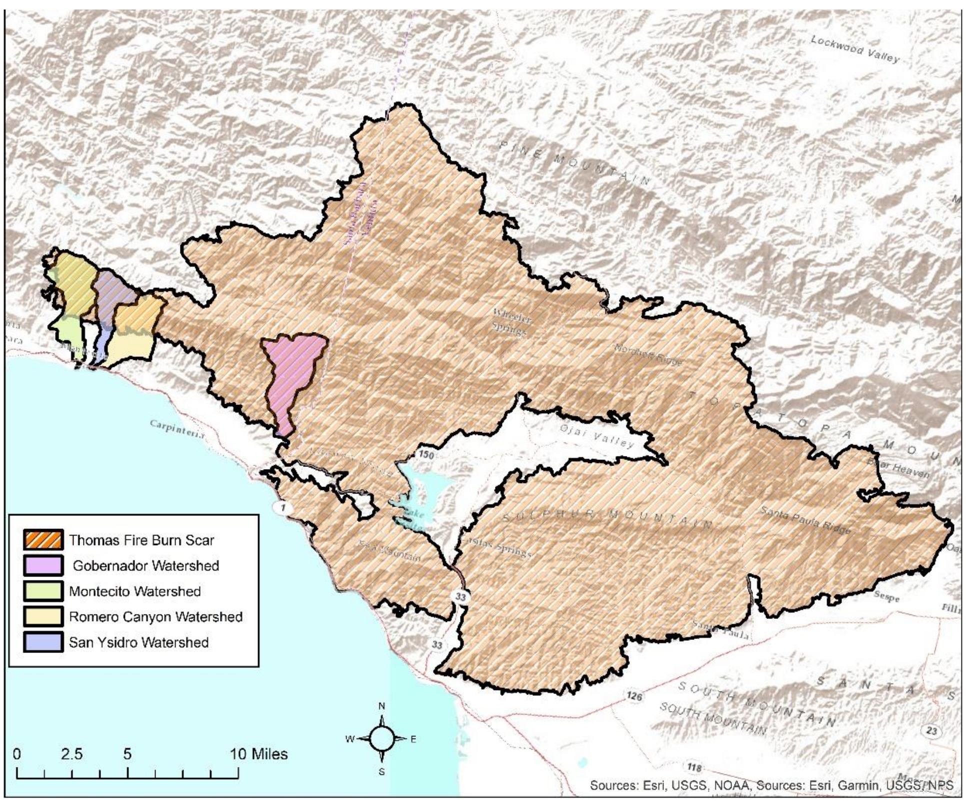

Figure 3.12 - Thomas Fire burn scar with study and reference watersheds overlaid.

Historical Debris Flows

The study watersheds have a history of flooding and debris flow, both in the geologic record and in historical times (Lancaster et al., 2020). Smaller sediment flows/landslides are presumed to have happened throughout history but are much harder to characterize quantitatively due to a lack of physical evidence lasting to the present day (Adamaitis, 2020). Evidence of a historic sequence of debris flows as old as 90,000 to 130,000 years has been identified in the same area as the study watersheds (Keller et al., 2020). Scattered boulders and old channel levees that were untouched by the 2018 Montecito debris-flow event are visible examples of major past events (Kean et al., 2019). Other visible examples include deposits from a massive debris flow with boulders up to 15 feet in diameter being present just west of Montecito at the confluence of Rattlesnake and Mission Creeks, just outside the study watersheds (Urban, 2004; Minor et al., 2009).

During the Randall Road Debris Basin excavation on San Ysidro Creek, evidence of a historic debris flow, including boulders up to 15 feet in diameter, estimated to be hundreds of thousands of years old, was uncovered along San Ysidro Creek (SBCFCD personal communication, 2021). Along Montecito Creek a debris flow runout stretching from the confluence of Hot Springs Creek and Montecito Creek down towards the ocean, about 2.25 miles, was discovered by a UCSB research team investigating the January 9th, 2018 Montecito debris flow. The historic debris flow along Montecito Creek was estimated to be between 1,000 to 2,000 years old (Keller et al., 2020). Of the 29 debris flow events recorded in Southern Santa Barbara County (Gaviota to Rincon Point) in the last 196 years, 19 events occurred in Montecito (Gurrola personal communication, 2021). Furthermore, five large, significant debris flow events were identified from these 19 events, including post-fire debris flow events in 1825, 1914, and 2018. A mean recurrence interval for Montecito events in the ~200-year record was determined to be 48 years for large debris flow events, with a minimum of 23 years and a maximum of 81 years (Gurrola personal communication, 2021).

Precipitation History

Santa Barbara County's precipitation patterns are characterized by dry, warmer summers and wet, cooler winters. Annual rainfall totals can vary considerably, with some years considerably above or below the average yearly rainfall of ~20 inches. The El Niño Southern Oscillation (ENSO) can influence weather patterns with El Niño years generally resulting in above-average annual precipitation and La Niña years in the inverse, although this is not always the case and this system still requires more study to understand implications for local precipitation that contributes to debris flows. Atmospheric river events driven by subtropical moisture also play a large role in the region's precipitation, with the storm front resulting in the 2018 Montecito debris flow driven by a narrow-band cold front enhanced by orographic lifting (Oakley et al., 2018). Minor to moderate storms can initiate mass wasting events, particularly if there has recently been a wildfire in the watershed, with debris flow initiation largely driven by 5- or 15-minute intensities rather than total precipitation of an individual storm event (McGuire and Youberg, 2020). Recent precipitation also plays a role with the saturation of soil or lack thereof, heavily influencing runoff, rill erosion, and sediment transport.

Summers in Montecito are warm and arid, while winters are cold, wet, and partly cloudy. Over the course of the year, the temperature typically varies from 42°F to 78°F, rarely falling below 34°F or above 84°F. The mean annual precipitation is 19.8 in. (SBCFCD, 2020), although annual precipitation can vary substantially (a maximum of 46.9 in. for 1998 and a minimum of 6.41 in for 2007) (Table 3.1). Over 90 percent of Santa Barbara's rainfall occurs during the 6-month (October to March) wet season, which lends to the study watershed's rivers, creeks, and streams being intermittent and only flowing for a few weeks or months after rainfall occurs (Hoover, 2020). Storms in the typical 6-month window can produce as much as 10 inches per storm, which is observed in 1995 but are typically less (Figure 3.13). The proximity of the Pacific Ocean tends to moderate Montecito's climate and temperatures near the coast, while adjacent steep mountain ranges paralleling the coast result in a significant orographic effect (Oakley et al., 2018). The orographic effect occurs when ocean storms are forced upward against the mountains resulting in increased precipitation with increasing elevation. In conjunction with the steep, short watersheds, this effect occasionally results in flash flooding along the county's south coast.

Table 3.1 - Santa Barbara Monthly Climate Summary. Source: (SBCFCD)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temp. (F)	64.9	65.6	66.8	69.0	69.9	72.4	75.9	77.1	76.7	74.4	70.9	66.4	**70.8**
Average Min. Temp. (F)	43.0	44.6	46.2	48.6	51.3	54.3	57.3	57.9	56.4	52.5	46.9	43.4	**50.2**
Average Total Precip (in.)	3.98	3.86	2.97	1.21	0.36	0.08	0.02	0.03	0.20	0.69	1.50	2.82	**17.73**

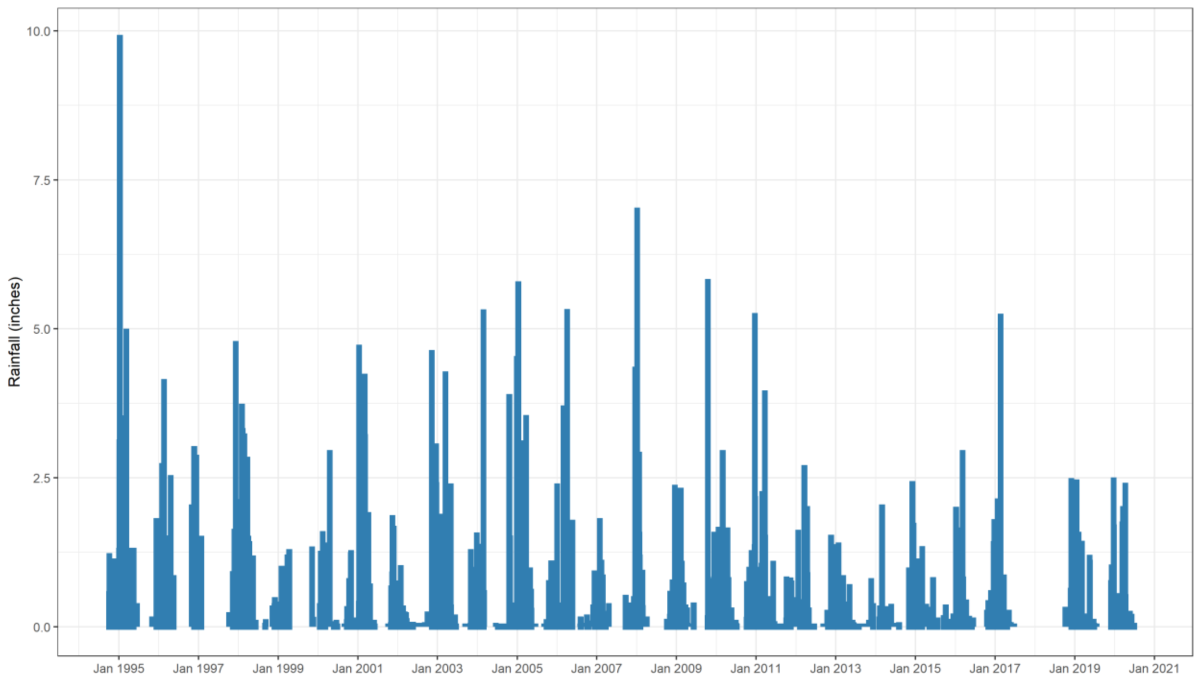

Figure 3.13 - Daily precipitation values from the Cold Springs Debris basin from the years of 1995 to 2020. Note that no data exists for this gauge for 2018. Source: (SBCFCD)

The 5 closest rain gauges in the area are located at the Cold Springs Basin, Summerland at the intersection of Vista Oceano Lane and Lambert Road, Pine Canyon off of route 166, Montecito near the debris basin off of Olive Mill Road, the KTYD radio tower off of Gibraltar Road and Doulton Tunnel (Figure 3.14). The average annual precipitation of the lowest elevation rain monitoring station is about 15 in/yr, while the highest elevation station is about 28 in/yr.

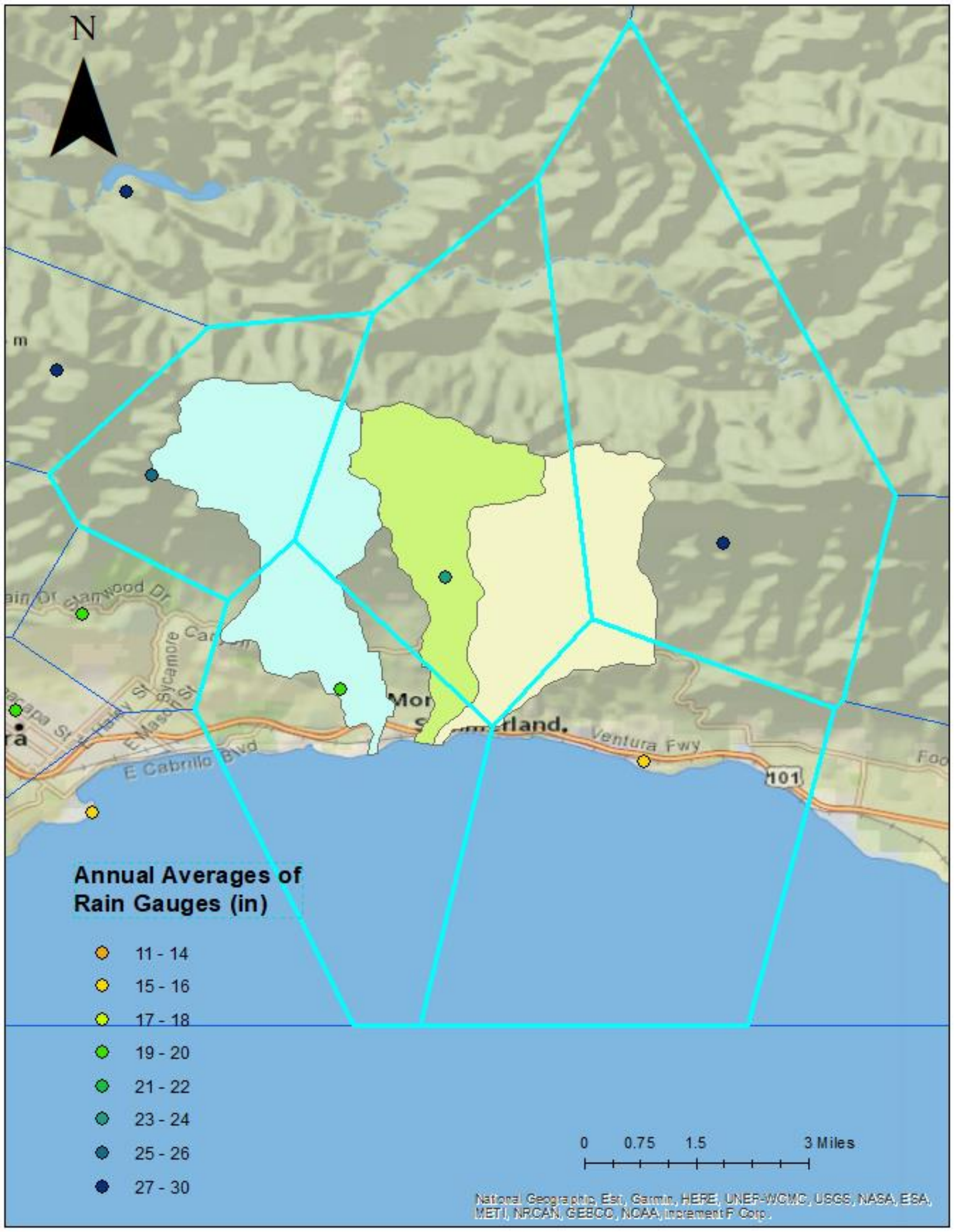

Figure 3.14 - Thiessen Polygons show the closest rain gauges for each watershed.

The variation can be observed in the data between stations of lower elevations near the coast and higher elevations inland. Assumptions of point rainfall data need to be interpolated over the watershed area. The Doulton Tunnel station is the highest elevation, and its rain gauge data shows higher values (Figure 3.15). The station located at the Cold Springs Debris Basin is an intermediate elevation and shows intermediate annual rainfall amounts (Figure 3.16). The Summerland rain gauge is the lowest elevation and closest to the coast and has the lowest annual rainfall totals (Figure 3.17). The intensities follow the same trend of increasing values as elevation increases when observing the 15-min intensities of the three stations (Table 3.2).

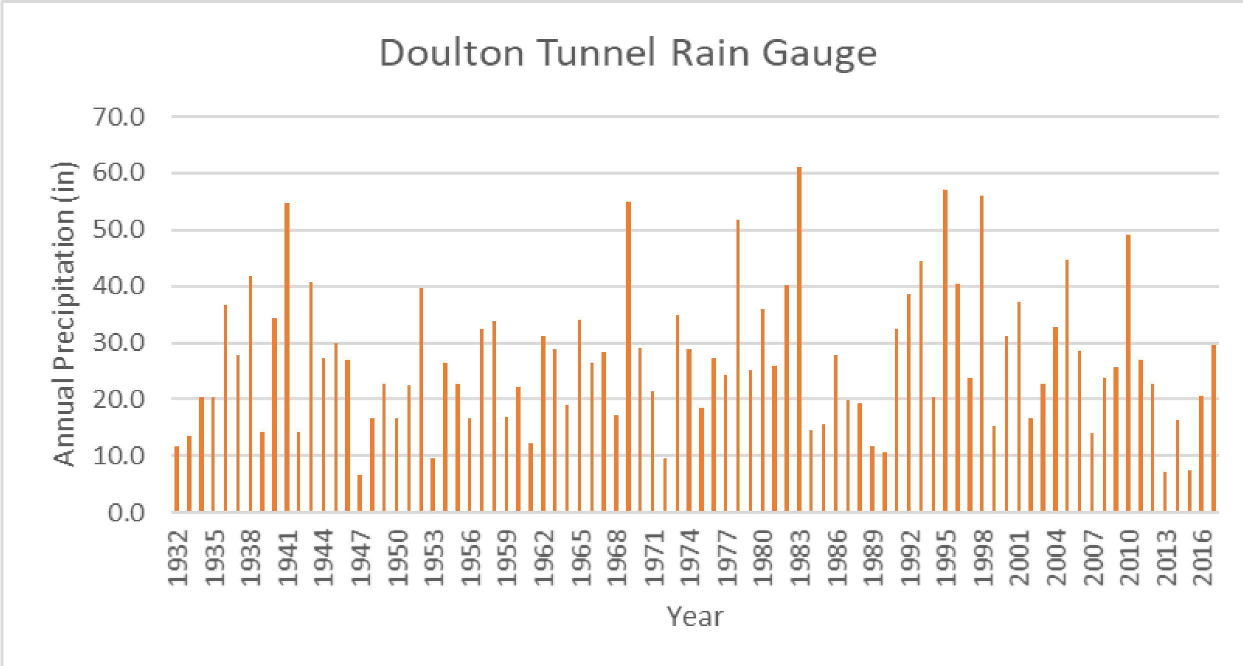

Figure 3.15 - Annual precipitation from the Doulton Tunnel rain gauge. Source: (SBCFCD)

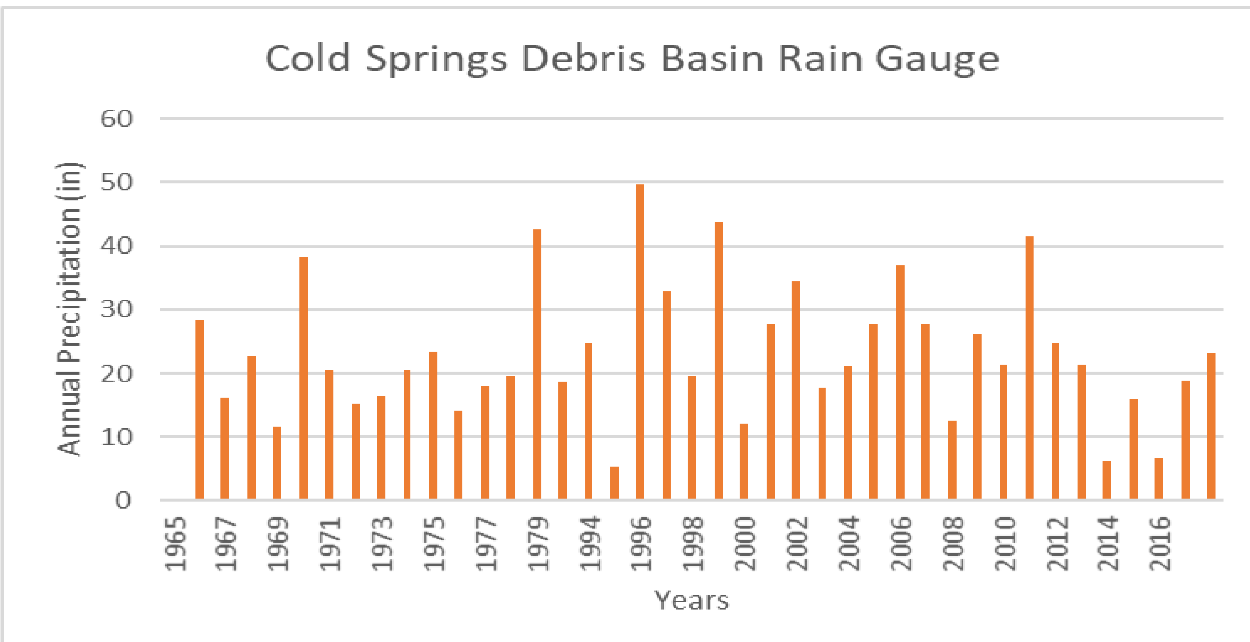

Figure 3.16 - Annual precipitation from the Cold Springs Debris Basin rain gauge. Source: (SBCFCD)

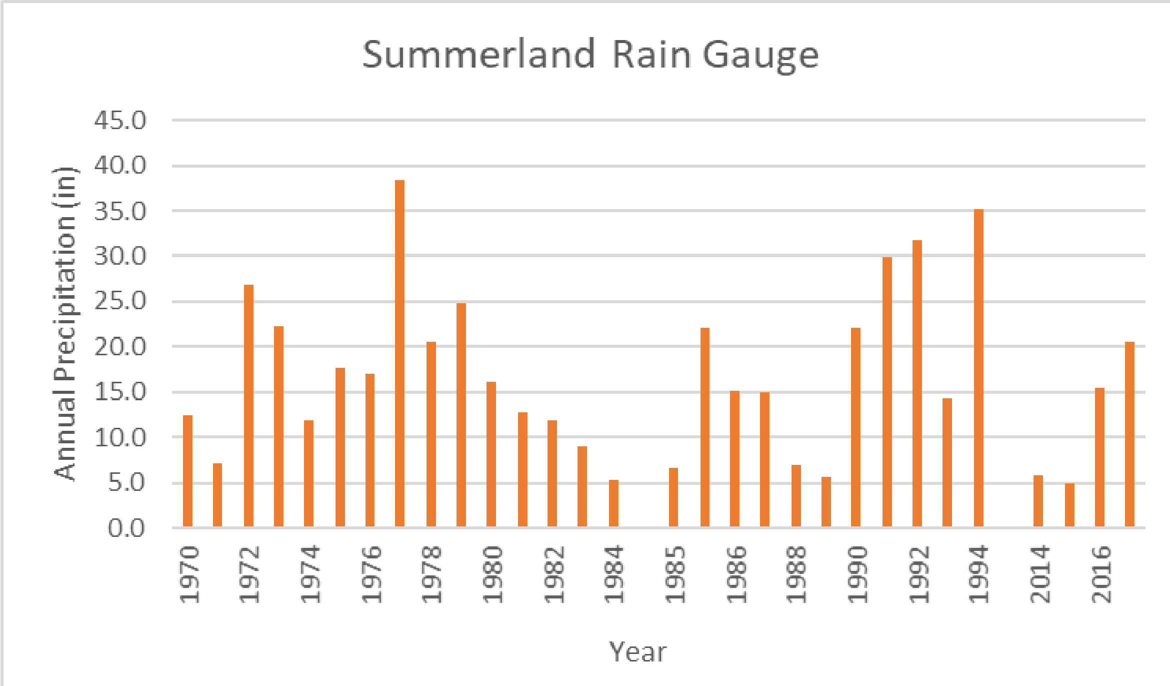

Figure 3.17 - Annual precipitation from the Summerland rain gauge. Source: (SBCFCD)

Table 3.2 - Average peak intensity for 3 stations near the watersheds and elevations.

Station	Annual average peak rainfall intensity (15min) (inches)	Average annual precipitation (inches)	Elevation (feet)
Carpinteria	0.28	17.2	30
Cold Springs	0.39	23.98	590
Doulton Tunnel	0.49	28.91	1775

Debris basin clearing typically takes place in the summer months to avoid complications from rainfall. From the periods 2008 to 2017, the Cold Springs Debris Basin required clearing after the rainy season of 2010 and 2011 (Figure 3.18). The figure below plots data for the Cold Springs debris basin that triggered desilting operations. Fires are also plotted on figure 3.18 to communicate the temporal relationship that burn scaring can have on sediment delivery. Basin clearing activities were triggered for two years after the 2009 Jesusita fire while, no desilting activities were triggered in the basin from 2013 to the events following the Thomas fire.

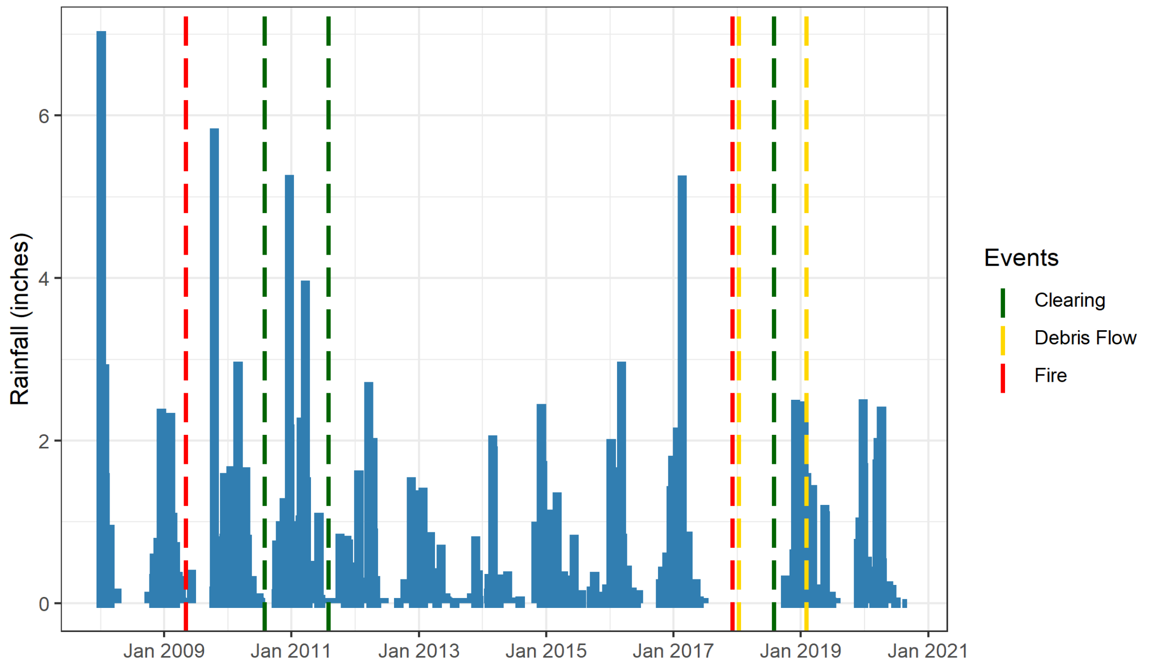

Figure 3.18 - Basin clearings are signified with green dotted lines and occur after the rainy seasons following a fire in the watershed. The yellow dotted lines show the selected debris flows of January 9th, 2018 and the San Ysidro event that occurred on February 2nd, 2019. *Note that no data exists for this gauge for 2018 and not all debris flow events are represented in this figure.*

As stated in table 3.2, annual peak rainfall intensity can range between 0.28 and 0.49 inches of accumulations in 15-min intervals, while individual storms can vary in intensity from <0.05 to 0.24 per 15-min interval (Figure 3.19). The figure below plots the rainfall intensity data associated with the February 2nd, 2019 event that resulted in the San Ysidro basin overflowing. Short-term high-intensity periods can be hidden in aggregated data, showing the need for individual storm analysis to be completed for debris flow threshold identification.

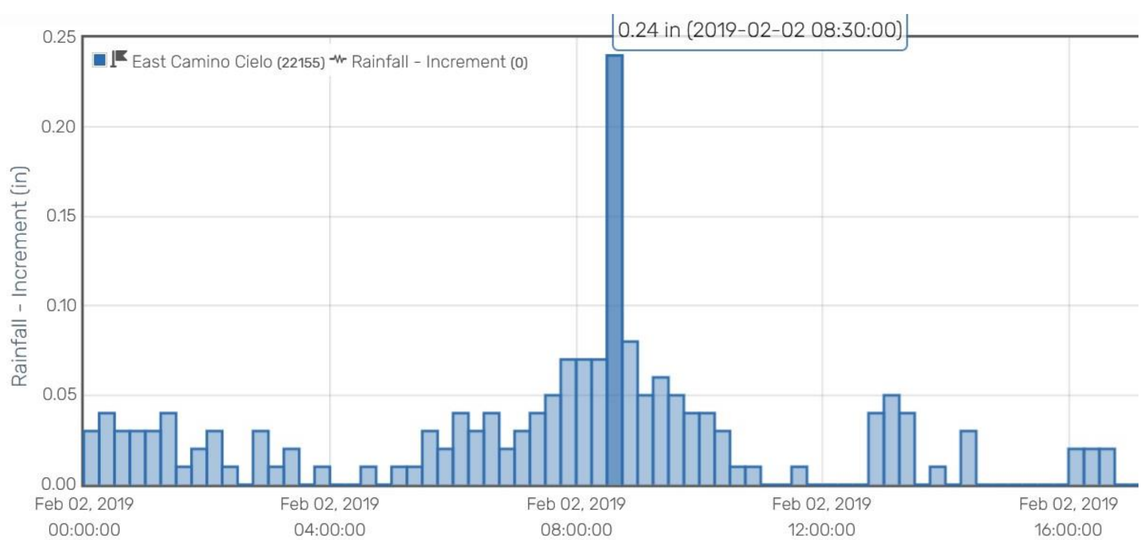

Figure 3.19 - Rainfall intensity in 15-min intervals reported in inches of accumulation for the San Ysidro debris flow event that occurred on February 2nd, 2019.

Non-Fire Debris Flow

While fire is a major driver of debris flow magnitude due to amplifying effects of vegetation loss and decreased water infiltration into hydrophobic soil, it is important to note that earth moving hazards can occur independently of fire. Generally, there is a correlation to precipitation, although this is not necessarily true for geophysical hazards such as earthquakes. The primary example of a major landslide event occurring independent of fire was the La Conchita landslide of 2005, which occurred in Ventura County. After sliding in 1995, the active slide lost stability in 2005 after 16.9 inches of rainfall over 15 days, resulting in 10 deaths and 13 homes being destroyed (Jibson, 2006). On a less localized scale, heavy rainfall can drive impacts to transportation corridors through fallen debris, localized flooding, and moving sediments, as shown by landslides and rockfalls along Highway 154 that often correlate to intense precipitation independent of preceding wildfire (Bolton, 2020).

Debris Basins Maintenance

SBCFCD conducts routine maintenance of Santa Barbara County debris basins under the 1996 Debris Basin Maintenance Plan and, more recently, the 2003 Debris Basin Maintenance Plan. The Updated Basin Maintenance and Management Plan (2021) builds upon the 1996 and 2003, and 2017 maintenance plans that describe the maintenance of the district's 17 debris basins along the south coast of Santa Barbara County (Figure 3.20 shows the eastern 11 basins). In 2016 SBCFCD collaborated with ACOE and NOAA Fisheries for management of critical habitat for the Southern California DPS for steelhead (O. mykiss) (SBCFCD, 2017). The outcome requires SBCFCD to implement a maintenance plan that enforces an upkeep plan that calls for establishing and continuing essential processes that are crucial to healthy habitat for endangered steelhead, including in the Montecito area study watersheds (SBCFCD, 2017).

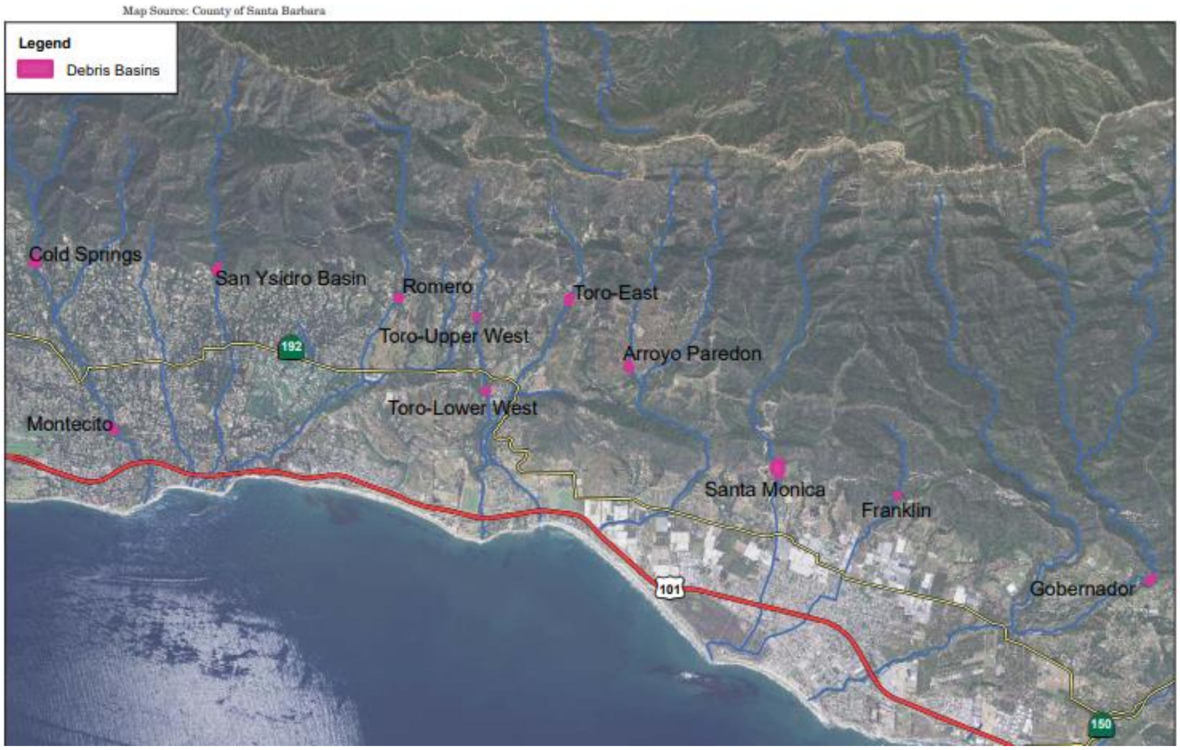

Figure 3.20 - Study watershed debris basin locations and 7 others. Source: (SBCFCD)

Routine Maintenance

General routine maintenance aims to allow retention of high-quality habitat within each of the basins between desilting events. It typically occurs between the months of August and November to avoid the rainy season and breeding seasons for birds and other wildlife. Routine maintenance of debris basins includes keeping the outlet works and other specific areas clear of obstructive vegetation to minimize plugging (SBCFCD, 2021). Maintenance of the outlet works will ensure that the basins allow all low and moderate flows to pass so that they don't incrementally fill in, which would reduce their effectiveness when needed. Routine maintenance may also include minor repairs to the grouted rock dam embankments and outlet pipe that occasionally experience erosion and need to be fixed to protect the structure from further erosion or failure.

Cold Springs Debris Basin

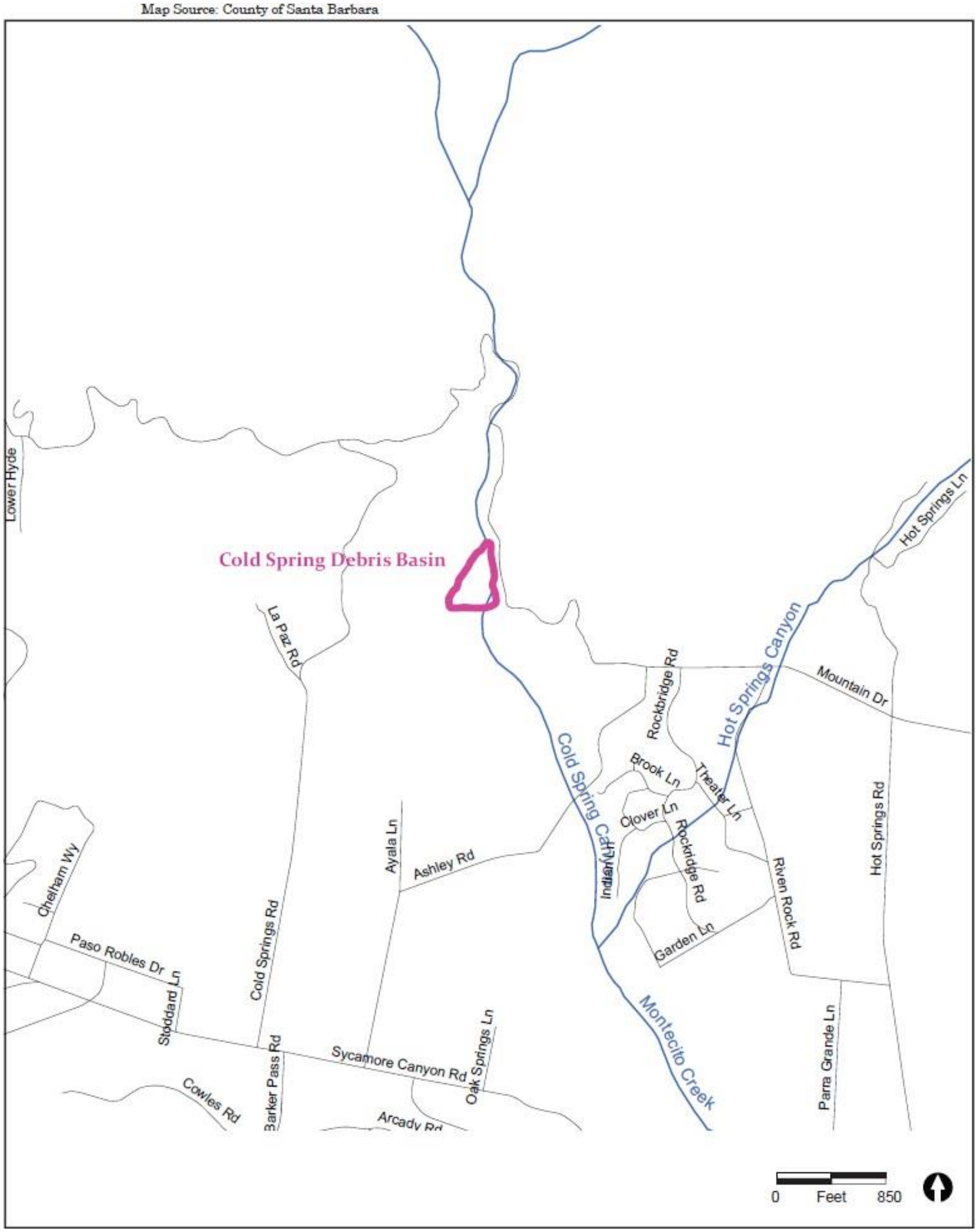

Figure 3.21 - Map of Cold Springs Debris Basin. Source: (SBCFCD)

The Cold Springs Debris Basin is located on Cold Springs Creek, a tributary of Montecito Creek (Figure 3.21, 3.22). It is a boxed outfall structure and is located west of East Mountain Drive. The Cold Springs Debris Basin's capacity was expanded to 20,000 yd^3 following the

2018 Montecito debris flow and SBCFCD currently plans to modify the basin to a slotted outfall. Refer to Figure 1.3 for an image of Cold Springs Debris Basin being excavated.

Figure 3.22 - Picture of Cold Springs Debris Basin.

Montecito Creek Debris Basin

Figure 3.23 - Location of Montecito Creek Debris Basin. Source: (SBCFCD)

The Montecito Creek basin is below the Colds Springs and Hot Springs reaches of Montecito Creek which takes up about 1400 acres in the watershed (Lancaster et al., 2020) (Figure 3.23). The Montecito Creek Debris Basin is located on Montecito Creek just east of Olive Mill Road and south of the Casa Dorinda retirement facility. Montecito Creek Debris Basin is an engineered facility that was completed in 2002 by SBCFCD after repeated flooding due to sedimentation in 1995 and 1998. The basin was designed to trap 5500 yd^3 of flood debris in anticipation of accelerated erosion of the watershed (Figure 3.24). The Debris Basin project includes a fishway along the east side of the basin, designed and implemented in consultation with the National Marine Fisheries Service (NMFS), to allow for fish passage. The upstream end of the basin involves the fishway merging back into the existing privately-owned concrete channel. This transitional area was further modified for improved sediment transport and fish passage in 2011 by constructing a slot and weir structure along the floor of the concrete channel (Figure 3.24). To date, the modification in 2011 has been successful in diverting sediment into the main basin rather than into the fishway. Past maintenance at Montecito Basin has also involved periodic sediment removal from the transitional area and the fishway, minor concrete sealing and drain repairs, and annual maintenance of a pilot channel through the main basin. Construction of the Montecito Creek Debris Basin was completed in September 2002. Once construction was complete, the district began restoration along the basin slopes and overbank areas surrounding the basins. Because steelhead trout are known to inhabit Montecito Creek, construction of the debris basin incorporated a fishway along the east bank of the facility. This fishway consists of resting pools at the upstream and downstream end of the basin and a concrete lined channel with baffles inserted at intervals to slow water velocities through the fishway to allow steelhead to navigate both upstream and downstream.

The Montecito Creek Debris Basin is maintained on a routine basis to ensure that it will be able to function properly when there are high flows. Long-term maintenance includes complete debris removal after the basin fills or after there is a significant fire in the watershed. This will be necessary after the basin fills approximately 25 percent or roughly every 5 to 10 years given average or less rainfall; the basin may have to be cleaned more than once on excessive rainfall years. Complete debris/vegetation removal will also be conducted if there is a significant fire in the watershed. Access will be taken from Olive Mill Road and the adjacent gravel roadway leading to the downstream end of the basin. Debris will be hauled to an appropriate disposal site after desilting.

Figure 3.24 - Montecito Creek debris basin. Source: (SBCFCD)

San Ysidro Creek Debris Basin

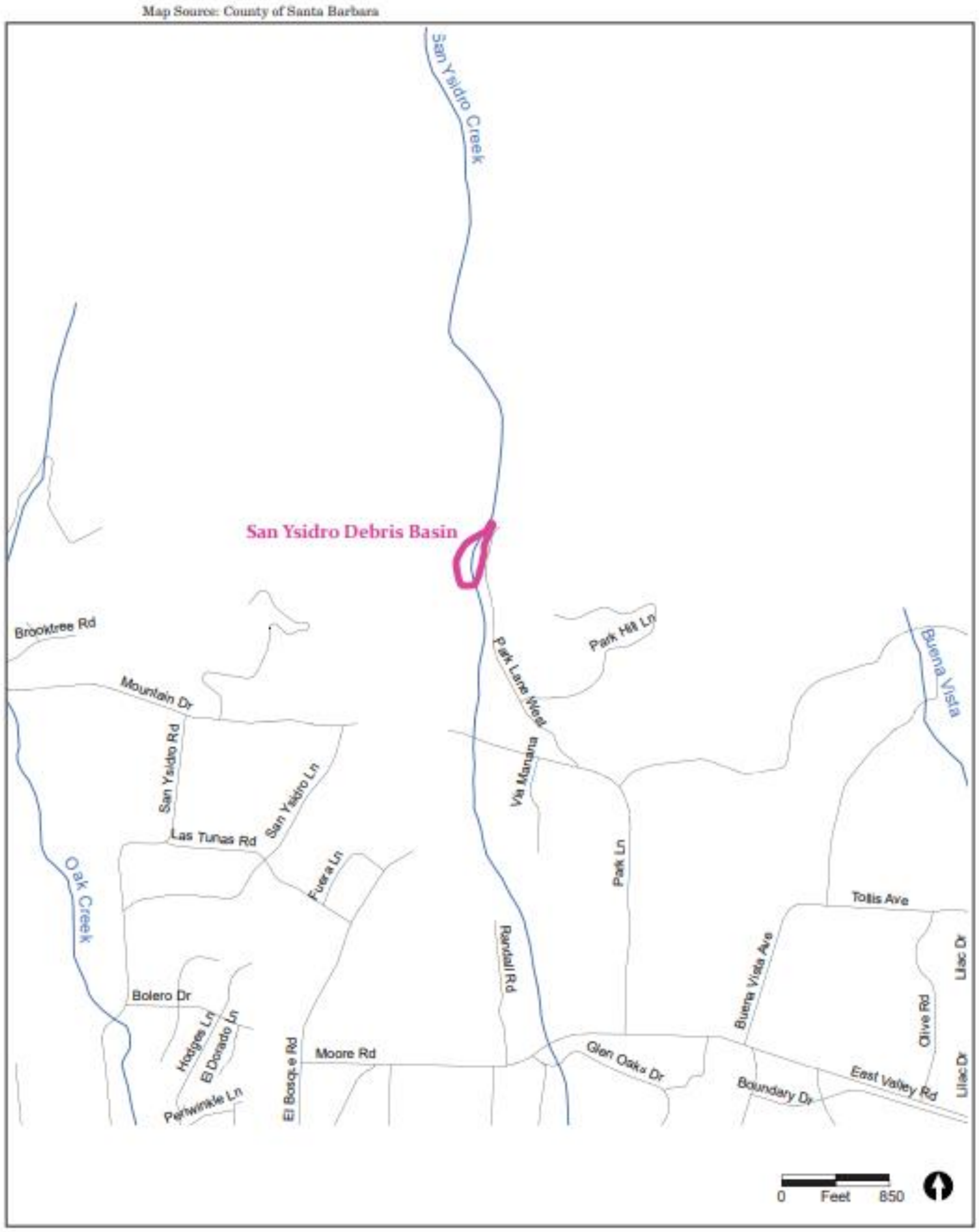

Figure 3.25 - Location of San Ysidro debris basin. Source: (SBCFCD)

San Ysidro Creek originates in the foothills of the Santa Ynez Mountains and drains a 2,621-acre watershed capable of producing 3500 cubic feet per second (cfs) during a 100-year return period precipitation event (SBCFCD, 2021). A well-developed riparian corridor exists to the north of the basin with chaparral habitat. The San Ysidro Creek Debris Basin is located on San Ysidro Creek at the end of West Park Lane in Montecito (Figure 3.25). The basin is surrounded by eucalyptus trees with the dam located at the south end (Figure 3.26). The basin was designed to trap 11,000 yd^3 of flood debris in anticipation of accelerated erosion of the fire-scorched watershed. The basin was maintained on an annual basis after construction until 1987. Between 1987 and 1994, the basin was maintained on an as-needed basis. Desilting projects occurred in 1969, 1978, 1983, twice in 1995, 1998, and 2005 (SBCFCD, 2021).

San Ysidro Basin was scheduled to be removed during the Fall of 2019. However, following the 2018 debris flow, SBCFCD decided to retain the basin and modify it from a boxed outfall to a slotted outfall to facilitate fish passage. This modification will be similar to the existing modification of the Gobernador Creek Debris Basin.

Figure 3.26 - San Ysidro debris basin. Source: (SBCFCD)

Randall Road Debris Basin

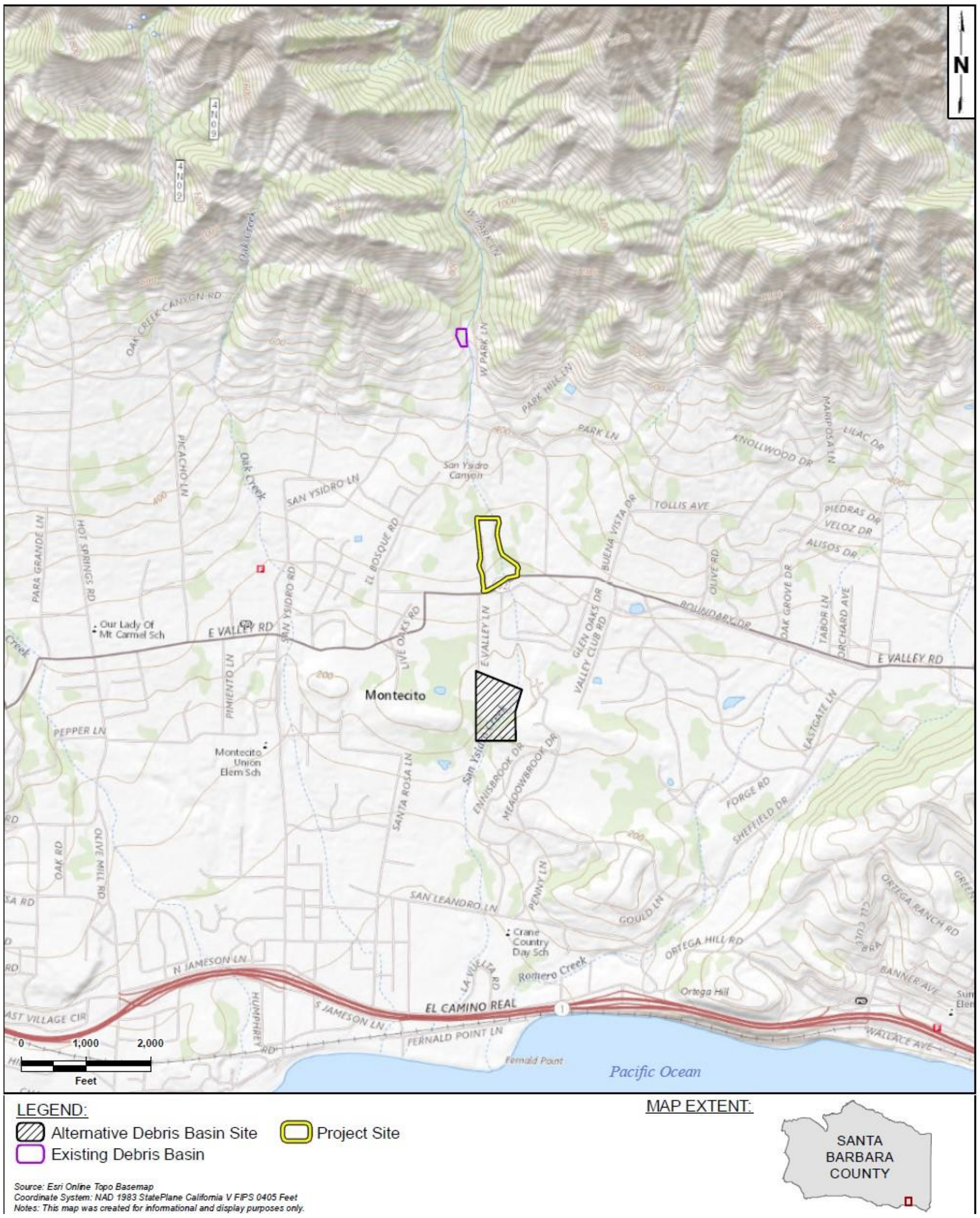

Figure 3.27 - Randall Road Debris Basin location. Source: (SBCFCD)

Following the 2018 Montecito debris flow, SBCFCD, in partnership with various entities including the federal government and a local non-profit Partners for Community Renewal Santa Barbara County, constructed the Randall Road Debris Basin on seven parcels on Randall Road just west of San Ysidro Creek (Figure 3.27). The area around Randall Road was heavily impacted during the 2018 Montecito debris flow, with the homes along Randall Road destroyed. The Randall Road project is effectively the re-expansion of the riparian corridor to achieve flood control benefits. Figure 3.28 shows an aerial view of the Randall Road Debris Basin looking south with San Ysidro Creek on the left. Randall Road is an example of a public-private partnership leveraging federal support to achieve community resiliency.

Figure 3.28 - Randall Road Debris Basin. (SBCFCD)

Romero Creek Debris Basin

Map Source: County of Santa Barbara

Figure 3.29 - Romero Creek Debris Basin location. Source: (SBCFCD)

Romero Creek originates in the foothills of the Santa Ynez Mountains and drains a 1,303-acre watershed capable of producing 3400 cfs during a 100-year return period precipitation event (SBCFCD, 2021). The Romero Creek Debris Basin is located on Romero Creek just east of 975 Romero Canyon Road in Montecito (Figure 3.29). A small tributary enters the basin from the east, and Romero Creek flows into the basin from the north. A well-developed riparian corridor exists to the north of the basin (Figure 3.30). The dam is located at the south end of the basin. Romero Creek Debris Basin is an engineered facility built in 1971 by ACOE after the Romero Fire burned a large percentage of the watershed. The basin was designed to trap 27,000 yd^3 of flood debris in anticipation of accelerated erosion of the denuded watershed (SBCFCD, 2017). The basin has been maintained on an as-needed basis since 1994. Major desilting projects occurred in 1969, 1978, 1983, twice in 1995, 1998, and 2005. The Romero Creek Debris Basin is maintained on a routine basis to ensure that it is able to function properly when there are high flows. Long-term maintenance includes complete debris removal after the basin fills or after there is a significant fire in the watershed. Routine maintenance consists of maintaining a 15-foot-wide pilot channel from the upstream end of the basin to the outlet works. The 48-inch outlet pipe and the grouted rip-rap spillway are maintained on an as-needed basis. Typically, maintenance consists of repairing the outlet pipe and spillway when they are cracked or chipped by pouring more concrete and adding rip-rap. Long-term maintenance consists of complete debris removal from the basin. This will be necessary after the basin fills approximately 25 percent or roughly every 5 to 10 years. Complete debris/vegetation removal will also be conducted if there is a significant fire in the watershed and debris will be hauled to an appropriate disposal site after desilting.

Figure 3.30 - Romero Creek Debris Basin. Source: (SBCFCD)

Gobernador Creek originates in the foothills of the Santa Ynez Mountains and drains a 5,086- acre watershed capable of producing 4900 cfs during a 100-year return period precipitation event (SBCFCD, 2021). The Gobernador Creek Debris Basin is located on Gobernador Creek, approximately 1,000 feet north of 7000 Gobernador Canyon Road (Figure 3.31). Gobernador Creek Debris Basin is an engineered facility that was built in 1971 by ACOE after the Romero Fire burned a large percentage of the watershed. The basin has been maintained under the current program since 1996. Major desilting projects occurred in 1969, 1978, 1983, twice in 1995, 1998, 2005, and 2018.

Gobernador Creek Debris Basin

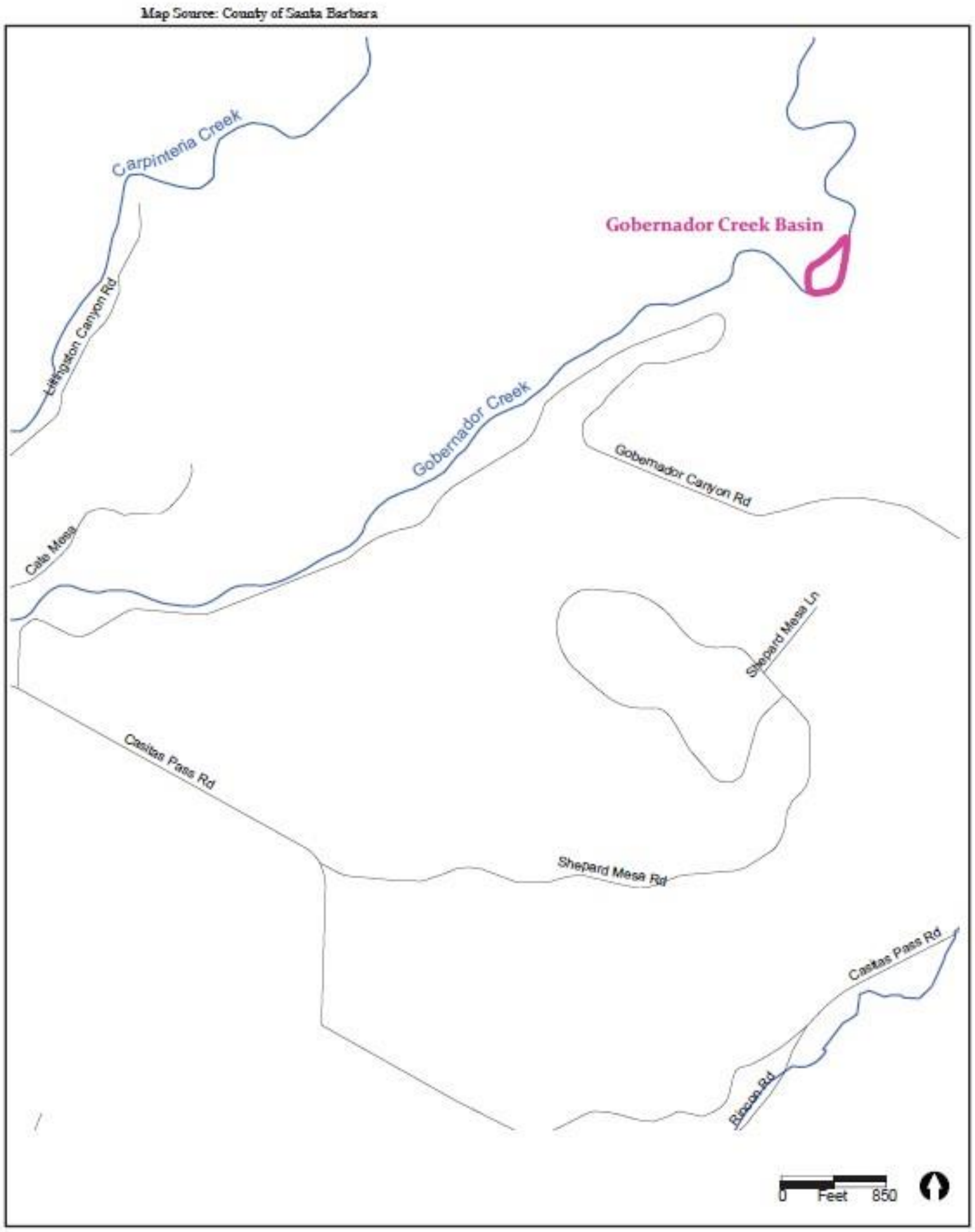

Figure 3.31 - Map of Gobernador Debris Basin. Source: (SBCFCD)

Gobernador Creek originates in the foothills of the Santa Ynez Mountains and drains a 5,086- acre watershed capable of producing 4900 cfs during a 100-year return period precipitation event (SBCFCD, 2021). The Gobernador Creek Debris Basin is located on

Gobernador Creek, approximately 1,000 feet north of 7000 Gobernador Canyon Road (Figure 3.31). Gobernador Creek Debris Basin is an engineered facility that was built in 1971 by ACOE after the Romero Fire burned a large percentage of the watershed. The basin has been maintained under the current program since 1996. Major desilting projects occurred in 1969, 1978, 1983, twice in 1995, 1998, 2005, and 2018.

In 2008 SBCFCD modified the Gobernador Creek Debris Basin from a boxed outflow (currently utilized on debris basins on the study watershed creeks) to a slotted outflow (Figure 3.32, 3.33). This was to achieve fish passage benefits while maintaining flood control capabilities. The Gobernador Debris Basin performed very well during the 2018 debris flow (SBCFCD personal communication, 2021).

Figure 3.32 - Slotted outfall on Gobernador, May 2021. Source: Sedimetrics

Figure 3.33 - Gobernador Slotted Outfall. Source: (SBCFCD)

Ringnets

The Partnership for Resilient Communities (TPRC) is dedicated to reducing risks to the Montecito community from natural hazards and identified ringnets higher in the study watersheds to possibly slow the speed of materials in future potential debris flow events, particularly large boulders and woody debris. The ringnets are planned to be installed temporarily and are slated for removal when vegetation higher in the watersheds has recovered adequately to reduce sediment transport (Figure 3.34). Six ringnets were installed on private property due to the efforts of TPRC.

Figure 3.34 - Ringnets on Cold Springs Creek. Source: (SCHR)

Background of Sediment Management for Steelhead and Federally Protected Status

The lower sections of the creeks which comprise our study watersheds are all designated as critical habitats for the federally endangered Southern California steelhead trout (Oncorhynchus mykiss) (Figure 3.35). This distinct population segment (DPS) comprises naturally spawned anadromous steelhead hatched below natural and artificial barriers ranging from the Santa Maria River at the San Luis Obispo-Santa Barbara County line in the north to the US-Mexico border at the Tijuana River in the south (NOAA Fisheries, 2022). In 2005 NOAA designated critical habitat for the seven evolutionarily significant units of Pacific salmon and steelhead in California, which includes the DPS of Southern California steelhead. Steelhead was historically numerous in the rivers and creeks of Southern California, though their numbers have drastically declined in the latter half of the 20th century into the 21st century, resulting in the endangered listing under the Endangered Species Act (ESA). The Santa Ynez River in Santa Barbara County represented a major stronghold for the Southern DSP, although the construction of Bradbury Dam in the 1950s now creates an impassable barrier to fish passage (Alagona et al., 2012). Multiple creeks (including Montecito, San Ysidro, and Romero) were designated as critical habitat as of 2005. The modification of

Gobernador debris basin on Gobernador Creek in the Carpinteria Creek watershed was primarily motivated by improved fish passage for steelhead.

Figure 3.35 - Picture of Steelhead (Oncorhynchus mykiss). Source: (Pacific Grove Museum of Natural History)

Planned Future Infrastructure and Debris Basins Modifications

In 2014 the National Marine Fisheries Service (NOAA Fisheries or NMFS) delivered a jeopardy biological opinion (BO) finding SBCFCD in violation of their ESA obligations to protect steelhead trout along several creeks in Santa Barbara County. As a result of this BO, SBCFCD completed the planning process to remove five debris basin structures, including Cold Springs Debris Basin on Cold Springs Creek, which flows into Montecito Creek and San Ysidro Debris Basin (SBCFCD, 2017). Following the catastrophic 2018 Montecito debris flow, SBCFCD updated their modification plans to retain debris basin structures on Cold Springs and San Ysidro Creeks with future modification in the same style as the debris basin on Gobernador Creek (Figure 3.36). The planned modifications involve transitioning from a boxed outfall (Figure 3.37) to a slotted outfall, ideally facilitating fish passage and finer sediments to pass downstream through the debris basins. Finer sediment is needed in creeks to maintain the trout reproduction environment. Trout require pebble size grains for spawning, and keeping all sediment out of the river will lead to decreased habitat for fish and other marine species. Pebble count data indicate that suitable spawning substrates (3 to 100mm in size) make up about 56 percent of the substrate composition. Optimal substrate sizes (15 to 60mm) appear to make up approximately 44 percent of the substrate composition (Raleigh et al. 1984).

Figure 3.36 - Gobernador Before and After Modification. Source: (SBCFCD)

Figure 3.37 - Example of boxed outfall from San Antonio Debris Basin. Source: (SBCFCD)

SECTION 4 - Modeling

Methodology

Background

Erosion and sediment delivery are subjects of considerable study by physical scientists such as hydrologists, earth scientists, and geomorphologists. Because watershed sediments are a concern for the community at large, particularly in terms of human and environmental livelihood, they are also an interest of environmental managers and planners. Understanding the delivery of sediment has major implications for the protection of human health and property, maintenance of stream channels, and management of natural resources (Keller et al., 2020). Disturbance through fire increases the magnitude of sediment delivery and presents challenges to flood control operations, especially within chaparral landscapes such as those of Santa Barbara County’s south coast and the Santa Ynez Mountains (Wohlgemuth & Lilley, 2018). Sediment delivery in post-fire conditions of a burned watershed can be increased by an order of magnitude compared to an unburned watershed (Wagenbrenner & Robichaud, 2014). An added challenge is that the greatest risk from debris flows does not necessarily occur where events begin (i.e., in steep, less developed areas of a watershed) but rather downstream where population and infrastructure exist (Addison & Oommen, 2020). In low probability, high-risk scenarios such as the 2017 Thomas Fire and ensuing Montecito debris flows, sediment delivery can have deadly and destructive consequences.

Improved understanding of sediment delivery and debris flow mechanics can allow scientists, planners, and managers to better prepare and respond to low probability, high-risk events. This type of preparedness modeling has been used in the United States for natural disasters of all kinds. For example, the United States Geological Survey (USGS) and California Geologic Survey scientists utilized the Hazus model for tsunamis to model economic losses (Kean et al., 2019). Beyond taking measurements after debris flow to retroactively examine the physical dynamics involved in an event, policies and management that take continued prediction and preparedness into account can proactively protect life and property loss. Measuring the seismic signature of debris flows can estimate debris flow speed and provide a limited five-minute warning (with present instrumentation) or a wider ten-minute warning (with a seismic array designed for debris flows), better preparing at-risk populations for potential hazards (Lai et al., 2018). Following the Montecito debris flow, the Federal Emergency Management Agency (FEMA) reevaluated flood hazard zones and created post-burn curve numbers for runoff (Lancaster et al., 2021). The more accurately annual rain events and extreme events can be predicted, the better planners and the wider community can manage sediment annually and in response to moderate debris flow events while preparing for future catastrophes.

Modeling sediment delivery and post-fire debris flow can be challenging, particularly in the steep watersheds of the Southern California transverse mountain ranges. Ideally, site-specific mechanistic or empirical/statistical models can be developed to predict events within a particular watershed. Physically-based, numerical models for post-fire debris flow initiation are currently emerging. However, the input and computational requirements required to run these models over small study areas limit their applicability for the Montecito study watersheds (Kean & Staley, 2021). Similarly, there is insufficient data to construct a site-specific statistical model due to there being very few of these extreme events per century. Multiple parameters derived from site-specific measurements are necessary for statistical model construction. These include accurate estimates of sediment volumes from past events and site-specific watershed morphology, burn severity, and rainfall conditions (Garcia, 2008). Not all of these metrics are available for the study watersheds. Due to the unique geological characteristics of the transverse ranges, using proxy values from other California events presents an additional challenge. For example, sediment yields in the transverse ranges of Southern California are two- to tenfold greater than other areas of California (Warrick & Mertes, 2009).

With targeted, site-specific data collection, comprehensive sediment budgets can be developed in the future for the study watersheds. This would allow for further analysis that would inform management decisions and emergency planning (Kean & Staley, 2021). Currently, this ideal is difficult to attain since the data needed to calibrate these models is lacking. In the absence of site-specific models, empirical models have been constructed for the California transverse ranges (i.e., broader scale) through regression analysis. These models incorporate post-wildfire conditions and the magnitude of floods and debris flows (Gartner et al., 2014).

Empirical modeling of sediment delivery is used as our primary method to predict debris-flow volumes and probability in post-fire conditions within the study watersheds. We apply existing models developed by USGS for the transverse ranges in Southern California to evaluate various scenarios of current and future burn severity and rain intensity leading to debris flow events in the watersheds (Kean & Staley, 2021).

Due to the limitation of these models as discussed here and in the proceeding subsections, it should be made clear that the purpose of this analysis is to present results that inform a generalized understanding of post-fire debris flow probability and magnitude in these watersheds. As with any modeling, scale and scope are important considerations affecting the precision and accuracy of results. We apply spatially explicit results from broader analyses and down-scale them to the study watersheds. As a result, these results should not be used in place of a comprehensive hazard assessment, such as those produced by USGS (Kean & Staley, 2021).

Debris Flow Probability

To estimate annual debris-flow probability in the three study watersheds, we utilized a spatially explicit database (1 km spatial resolution) from a USGS study by Kean & Staley (2021) that considered the probability of debris flow throughout the transverse ranges of Southern California. The dataset was clipped to the County of Santa Barbara and then to our study watersheds in ESRI ArcGIS Pro. The dataset estimates debris flow probability, $P(DF)$, as a function of the probability of fire, $P(F)$, multiplied by the probability of a rainfall event with 15-minute peak rainfall intensity exceeding a debris flow initiation threshold intensity, $P(R > T)$. The peak 15-minute intensity is the peak rainfall intensity measured over a 15-minute duration. Equation 4.1 describes the relationship between the probability of debris flow and the probability of fire with an exceedance of an initiation threshold. Figure 4.1 illustrates the relationship with a Venn diagram conceptualization.

$$P(DF) = P(F \cap R > T)$$

Equation 4.1 *- General equation used to estimate probability of debris flow, where P(DF) is the probability of debris flow and P(F ∩ R > T) is the probability of the occurrence of a fire (denoted as P(F)) AND a rainfall event that exceeds an initiation threshold for for post-fire debris flow in a given year, denoted as* P(R > T). R *is peak 15-minute rainfall intensity, while* T *is the 15-minute rainfall intensity initiation threshold for a post-fire debris flow event (Kean & Staley, 2021).*

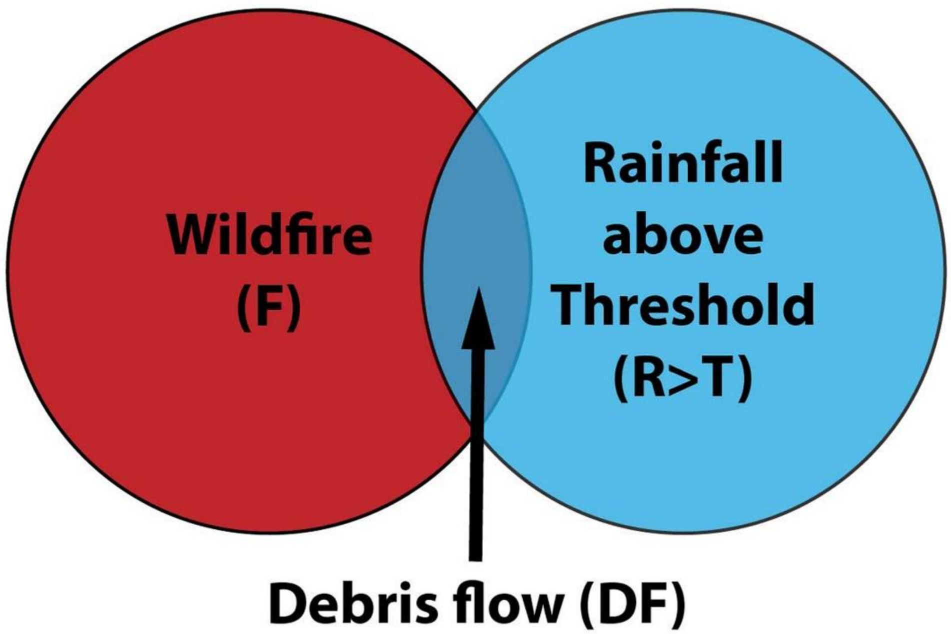

Figure 4.1 - Venn diagram conceptualization of the relationship of debris flow to wildfire and rainfall exceeding an initiation threshold (Kean & Staley, 2021).

Kean and Staley (2021) estimates *P(F)* using a California Department of Forestry and Fire Protection (CAL FIRE) database of historical fire perimeters from 1950 to 2018 (CAL FIRE, 2020). For a given cell, *P(F)* is approximated from Equation 4.2:

$$P(F) \approx \frac{n_{fires}}{n_{years}}$$

Equation 4.2 *- Equation used by Kean & Staley (2021) to estimate probability of fire, P(F), where nfires is the number of fires that have occurred at that the center of the cell over nyears (1950–2018), the years on the CAL FIRE historical record.*

This approach assumes that past fires have no substantial influence on future fire. The assumption holds for a generalization of these watersheds due to the fact that much of the vegetation found in the watersheds is adapted for fire (Barbour, 2000) and the watershed ecosystems have an anthropogenically-dominated fire regime which is limited by ignition (Keely & Syphard, 2017).

Kean & Staley (2021) estimate $P(R > T)$ from an empirical model and historical burn severity and precipitation frequency. First, the local rainfall intensity threshold (T) is estimated from a model developed by Staley et al. (2017), which calculates debris flow likelihood calibrated with southern California debris flow event data and geological characteristics for the affected watersheds (slope, soil characteristics, etc.). The representative threshold for each square kilometer cell was calculated from the median threshold for all stream segments in the cell (Kean & Staley, 2021). The probability of rainfall exceeding the 15-minute threshold at the cell was evaluated by comparing precipitation frequency data from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Perica et al., 2014). The Atlas 14 data shows rain event precipitation intensities associated with 1, 2, 5, 10, 25, 50, and 100-year recurrence intervals using local rain gauge records. The inverse of the recurrence interval corresponding to the threshold rain rates T_{50} and T_{84} represent $P(R > T_{50})$ and $P(R > T_{84})$, respectively (more explanation of T_{50} and T_{84} below) (Kean & Staley, 2021).

In order to estimate the $P(DF)$ under various conditions, Kean & Staley (2021) modified variables within the equation to account for factors that can change debris flow probability given future climate scenarios. The modified forms of the equation are described below in Table 4.1. For example, T_{50} is the threshold of initiation for a debris flow after a fire of moderate burn severity under current conditions. This was generated for each cell using median levels of historic burn severity. T_{84} represents future fire scenarios with a higher median burn severity. It was generated using the 84th percentile of historic burn severity. The rainfall threshold representative of a major debris flow that can escape a channel to cause greater damage is denoted as $3T$. A major debris flow is defined by Kean & Staley (2021) as events that have damaged 40 or more structures (Kean & Staley, 2021).

The impact of a change in the local precipitation regime due to climate change was considered by incorporating Representative Concentration Pathway (RCP) 4.5 into the conditions. RCP 4.5 is an intermediate emissions scenario described by a peak in emissions followed by a decline after the year 2040 (CalAdapt, 2022). Kean & Staley (2021) estimate a late century warming (2050 to 2099) using the four priority global climate models of the South Coast climate region. These models include: CanESM2 (Average), CNRM-CM5 (Cool/Wet), HadGEM2-ES (Warm/Dry), and MIROC5 (Complement) (CalAdapt, 2022). An 18 percent increase in precipitation intensity, denoted as 1.18R, is estimated by RCP 4.5 for the south coast region by the late century. This debris flow probability dataset aims to calculate the change in probability for at-threshold and major debris flows using that 18 percent precipitation intensity increase (Kean & Staley, 2021).

In our analysis, we examine whether a change in watershed debris flow probability occurs as a result of an increase in fire severity or rainfall intensity. This is determined by comparing the various scenarios represented in the Kean & Staley (2021) dataset as tabulated in Table 4.1. The results of this prediction analysis should be interpreted somewhat cautiously. Estimating changes in future fire and precipitation regimes and then forecasting changes in debris flow probability and magnitude is difficult due to the complexity of combined effects and relationships between climate, vegetation, erosion, and anthropogenic factors (Kean & Staley, 2021). We discuss the uncertainty by using the current P(F) metric in place of a more accurate estimation of the future conditions and projected precipitation predictions for future debris flow estimations in the modeling and climate change discussion sections of this report. However, this analysis is useful in describing the sensitivity of debris flow probability and magnitude to potential changes in fire and precipitation regimes, which can help form a general understanding of climate change impacts on debris flow.

In a recent evaluation of the probability model's performance under current conditions, Swanson et al. (2022) reported that the model performed well at predicting (post-hoc) the January 9th, 2018, post-fire debris flows in watershed regions affected by the Thomas Fire (Santa Barbara, Juncal Canyon, Matilija Canyon, Ojai/Nordhoff Ridge, and other areas). Using receiver operating characteristic (ROC) analysis, the study compared the rates of true positives and true negatives and false positives and false negatives in the predictive results for cells with rainfall exceeding thresholds associated with 50 percent probability of debris flow. The analysis found that the sensitivity of the model, which is the fraction of true positives to the total number of true positives and false negatives, was 0.98 for all the regions (1.0 = perfect prediction). Of 857 results, there were only 2 false negatives. The accuracy metric, which is the fraction of true negatives and true positives to the total number of true positives and true negatives and false positives and false negatives in the results (1.0 = perfect prediction), ranged from 0.28 to 0.85. The accuracy suffered most from several false positives. However, from the conservative standpoint of hazard assessment, which mostly considers the importance of the specificity metric, the model performs well (Swanson et al., 2022).

Table 4.1 - Parameters used in probability modeling. Source: (Forecasting the Frequency and Magnitude of Postfire Debris Flows Across Southern California, (Kean & Staley, 2021).

P(DF)	Conditions	Figures	Description
1. $P(F)P(R > T_{50})$	Present	4.4	Probability of debris flow given local precipitation frequency and median of historical burn severity
2. $P(F)P(R > 3T_{50})$	Present	4.6	Probability of major debris flow given local precipitation frequency and median of historical burn severity
3. $P(F)P(R > T_{84})$	Future w/higher burn severity	4.5	Probability of debris flow given local precipitation frequency and 84th percentile of historical burn severity
4. $P(F)P(R > 3T_{84})$	Future w/higher burn severity	4.8	Probability of major debris flow given local precipitation frequency and 84th percentile of historical burn severity
5. $P(F)P(1.18\ R > T_{50})$	Future w/higher rainfall severity	4.5	Probability of debris flow given median of historical burn severity and 18 percent increase in precipitation intensity based on RCP4.5 climate projections
6. $P(F)P(1.18\ R > 3T_{50})$	Future w/higher rainfall severity	4.8	Probability of major debris flow given median of historical burn severity and 18 percent increase in precipitation intensity based on RCP4.5 climate projections

Debris Flow Magnitude

To estimate the potential magnitude of a debris flow in the watersheds, we use an empirical, multivariate regression model shown in Equation 4.3 that was developed by Gartner et al. (2014) to predict debris flow volume within two years of a fire. This model was calibrated using databases of measured volumes of sediment deposited during storm events two years after a fire, as well as physical variables influencing debris flows in the Southern California transverse ranges (Gartner et al., 2014).

$$\ln(V) = 4.22 + \left(0.13 \times sqrt(ElevRange)\right) + (0.36 \times \ln(HMkm)) + \left(0.39 \times sqrt(i15)\right)$$

Equation 4.3 *- Gartner et al. (2014) equation used to estimate debris flow magnitude (volume).*

Sediment volumes were measured by tallying the number of trucks filled with sediment cleared from debris basins or comparing aerial surveys of full and empty basins. The physical watershed variables were measured in the field or using GIS and remote-sensing analyses of digital elevation models and spatially-explicit data for burn severity, rainfall, and soil properties (Gartner et al., 2014).

To construct the model, Gartner et al. (2014) first compiled a subset from 92 records of sediment volumes cleared from debris basins after individual storms and the associated measurements of watershed morphological characteristics, burn severities, times since fire, and rainfall conditions. Measurements were analyzed with multiple linear regression, and the independent variables were chosen based on their influence on the magnitude of debris flows from the databases. The model was then validated using 32 randomly selected volumes of sediment from the complete database. The associated independent variables from each storm event were used as inputs to test the model's ability to predict debris flow volumes for the given events. For all the storm events, the model predicted 100 percent of the observed volumes to within the 95 percent prediction interval and within 65,000 yd^3 of all the observed volumes (Gartner et al., 2014).

According to Gartner et al. (2014), peak 15-minute rainfall intensity is used due to the importance of short-duration, high intensity precipitation for debris-flow initiation. In some cases, debris flow initiation can occur within 5 minutes of continuous, high intensity rain but according to Kean et al. (2011), the 15-minute duration measurement best accounts for lag between a rain event and debris flow initiation. The other relationships, such as elevation range and area of hillslope burned, represent the importance of other physical variables in watershed debris flows (Gartner et al., 2014).

Gartner et al. (2014) reports a relatively high margin of error for the model stemming from the variability of observed volumes from the various reporting agencies. It should also be noted that because the January 9^{th}, 2018 Montecito debris flows exhausted much of the sediment supply from the study watersheds, the calculations generated from this analysis may overestimate the volumes that would occur during a post-fire debris flow in the near future (SBC OEM, 2021). This uncertainty was corroborated in personal communications with Dr. Ed Keller, geologist at the University of California, Santa Barbara, and Jason Kean, USGS research hydrologist.

In table 4.2 below, we tabulate the values used in the Gartner equation for the study area watersheds. First, we delineated the watersheds to the debris basins using the ESRI ArcGIS Pro watershed delineation wizard. Relief (feet) was calculated by clipping a 1-meter USGS digital elevation model (DEM) and subtracting the lowest elevation at the debris basin from the maximum elevation of each watershed. Watershed area burned (mi^2) was estimated by calculating the area within each watershed associated with a non-zero probability of annual moderate to high-severity burn from a dataset produced by Keane & Staley (2021). The spatially-averaged, upstream 15-minute peak rainfall intensity threshold for debris flow initiation in the study area was calculated by Keane & Staley (2021) as 0.866 in/hr.

Table 4.2 - Independent variables used for the Gartner equation for the three study watersheds (Montecito, San Ysidro, and Romero Creeks).

Watershed	Relief (*R*) (feet)	Area Burned (*Bmh*) (mi^2)	15 Min Peak Rainfall Intensity (*i15*) (in/hr)
Montecito	3250	3.7	0.866
San Ysidro	3110	3.0	0.866
Romero	2905	2.0	0.866

Results

Debris Flow Probability – Current Conditions

For post-fire debris flow probability under current precipitation conditions and burn severity, we generated the results for all three watersheds assuming a rain event exceeding the initiation threshold associated with median historical burn severity, denoted as T_{50}. We then produced the results for an initiation threshold associated with a *major* debris flow under current conditions, denoted as $3T_{50}$. These initiation thresholds were produced using the median of historic burn severity from CAL FIRE records (Kean & Staley, 2021). We show the estimated ranges of debris flow probability and *major* debris flow probability, as well as the range of values for $P(F)$, T_{50}, and $3T_{50}$ for all three watersheds combined in Table 4.3.

According to NOAA Atlas 14 data for a rain gauge located at Santa Barbara KYTD-FM radio towers (Lat: 34.4708, Long: -119.6769), which is roughly 2 miles northwest of the Cold Springs debris basin above Montecito, the 15-minute rainfall intensity associated with a 1-year recurrence interval is 1.34 in/hr (Perica et al., 2014). Kean & Staley (2021) used the local NOAA Atlas 14 data to interpolate the precipitation pattern across the grid (Kean & Staley, 2021).

Table 4.3 - Estimated range of debris flow and major debris flow probability for the study watersheds given current local precipitation conditions and median historical burn severity.

Watersheds (Combined) – Current Conditions					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** P(F) x P(R >T_{50})	**Major Debris Flow** P(F) x P(R >$3T_{50}$)
Min.	0	0.69	2.06	0	0
Max.	0.043	1.54	4.63	0.043	0.009
Mean	0.022	0.90	2.70	0.022	0.004
Std. Dev.	0.013	0.19	0.58	0.013	0.003

For the three watersheds combined, the probability of debris flow, $P(DF) = P(F)P(R > T_{50})$, ranged from 0 to 4.3 percent, with a mean of 2.2 percent (SD = 1.3) (Figure 4.2).

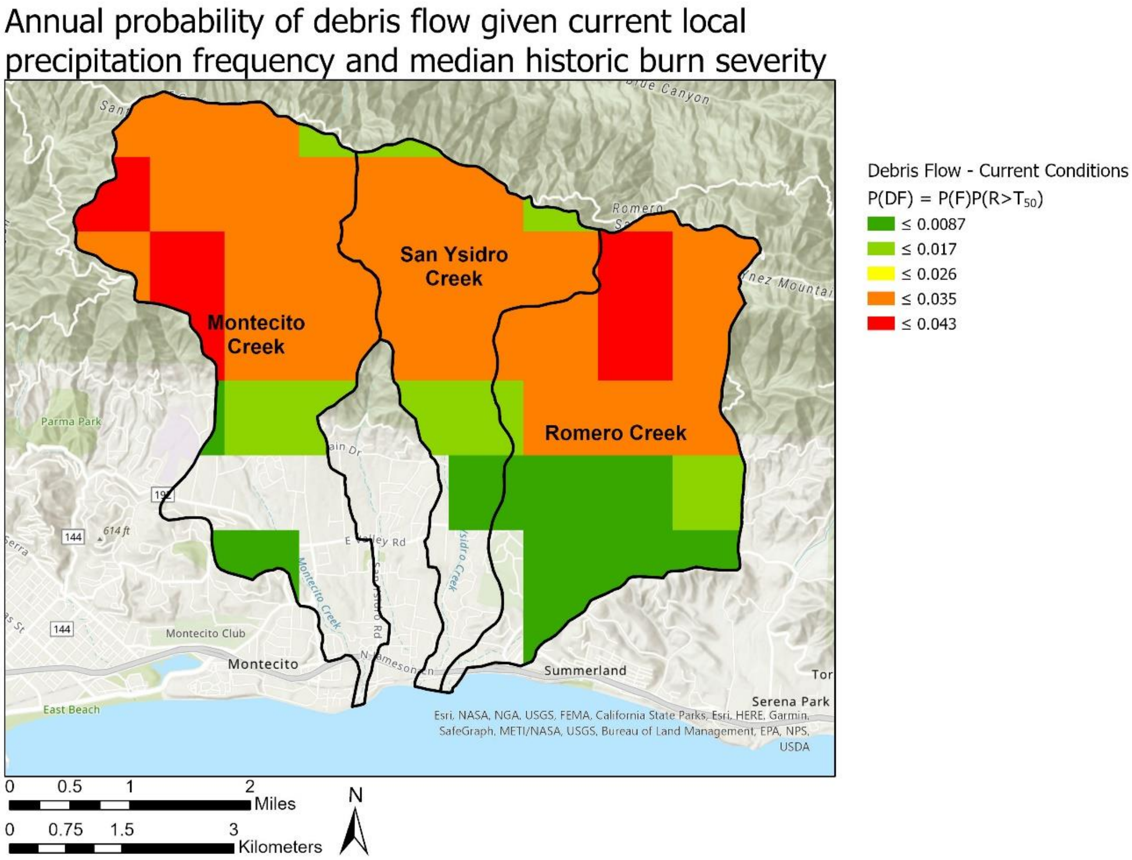

Figure 4.2 - The probability of debris flow, $P(DF) = P(F)P(R > T_{50})$, within the study watersheds given current local precipitation frequency and median historic burn severity.

For the watersheds combined, the probability of a *major* debris flow, $P(DF) = P(F)P(R > 3T_{50})$, ranged from 0 to 0.9 percent, with a mean of 0.4 percent (SD = 0.3).

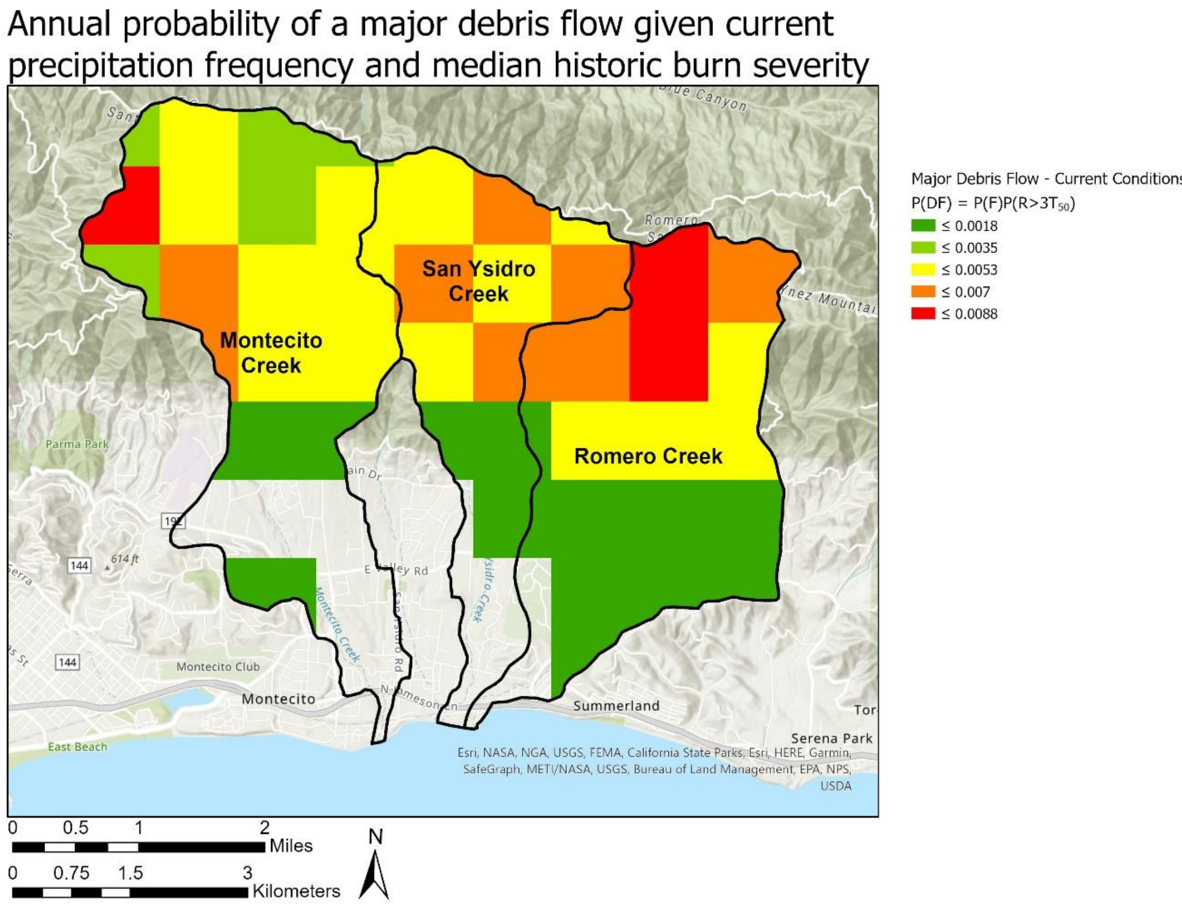

Figure 4.3 - The probability of a major debris flow, *$P(DF) = P(F)P(R > 3T_{50})$*, within the study watersheds given current local precipitation frequency and median historic burn severity. *Note: The visual color scale for major debris flow likelihood is based on equal interval classification using minimum and maximum values across the three watersheds. The scale varies between the climate conditions (i.e., current, future fire, and future precipitation intensity).*

We show the estimated minimum, maximum, and mean probabilities for a debris flow and a *major* debris flow, as well as the range of values for *$P(F)$*, *T_{50}*, and *$3T_{50}$* for each watershed individually within the appendix.

Debris Flow Probability – Future Fire (Higher Burn Severity)

We then compared the results to the initiation thresholds of high severity burn, accounted for by the 84th percentile of historic burn severity, denoted as T_{84} (Table 4.4). There was no change in the probability of a debris flow for the watersheds in this study between the T_{50} and T_{84} thresholds. The minimum probability of debris flow for both thresholds was 0 while the maximum was roughly 4.3 percent for the watersheds combined (Figure 4.4). The mean probability was 0.4 percent (SD = 0.3). The similarity of the results is due to the fact that the recurrence interval for a peak rainfall intensity exceeding either threshold was 1 year (probability ≈ 100 percent in a given year), so the probability of debris flow relies on the chance of fire in this model.

Table 4.4 - Estimated range of debris flow and major debris flow probability for the study watersheds given local precipitation conditions and 84th percentile historical burn severity.

Watersheds (Combined) – Future Fire (Higher Burn Severity)					
	P(F)	**T_{84}** (in/hr)	**$3T_{84}$** (in/hr)	**Debris Flow** $P(F)P(R > T_{84})$	**Major Debris Flow** $P(F)P(R > 3T_{84})$
Min.	0	0.59	1.78	0	0
Max.	0.043	1.10	3.30	0.043	0.016
Mean	0.022	0.74	2.23	0.022	0.007
Std. Dev.	0.013	0.12	0.37	0.013	0.005

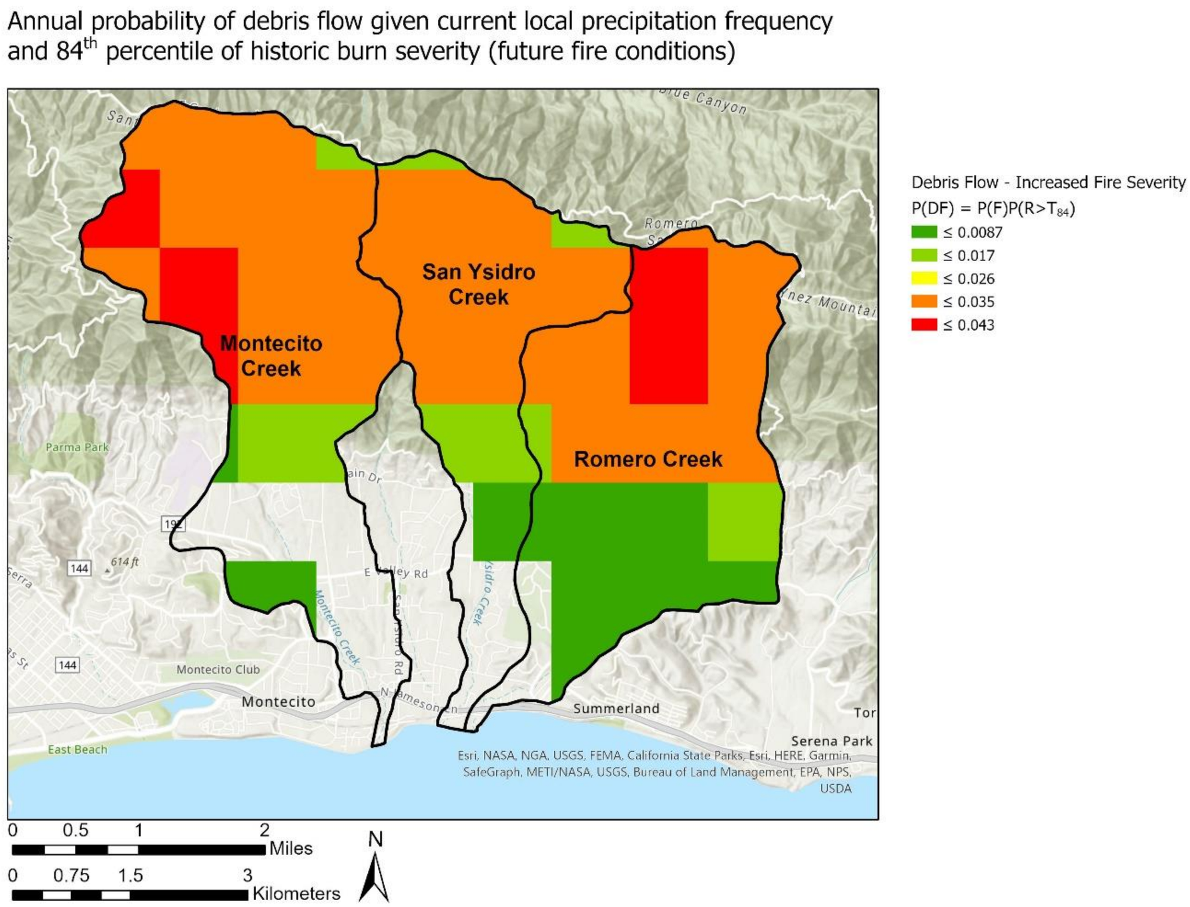

Figure 4.4 - The probability of debris flow, $P(DF) = P(F)P(R > T_{84})$, within the study watersheds given current local precipitation frequency and 84th percentile of historic burn severity.

The probability of *major* debris flows for increased burn severity, with a peak 15-min initiation threshold denoted as $3T_{84}$, ranged from 0 to 1.3 percent with a mean of 0.6 percent (SD = 0.3) (Figure 4.5). The maximum and mean *major* debris flow probabilities for increased burn severity are higher compared to current conditions (1.3 and 0.7 percent compared to 0.9 and 0.4 percent, respectively) due to the fact that the threshold for a *major* debris flow is decreased after a higher severity burn (Kean & Staley, 2021).

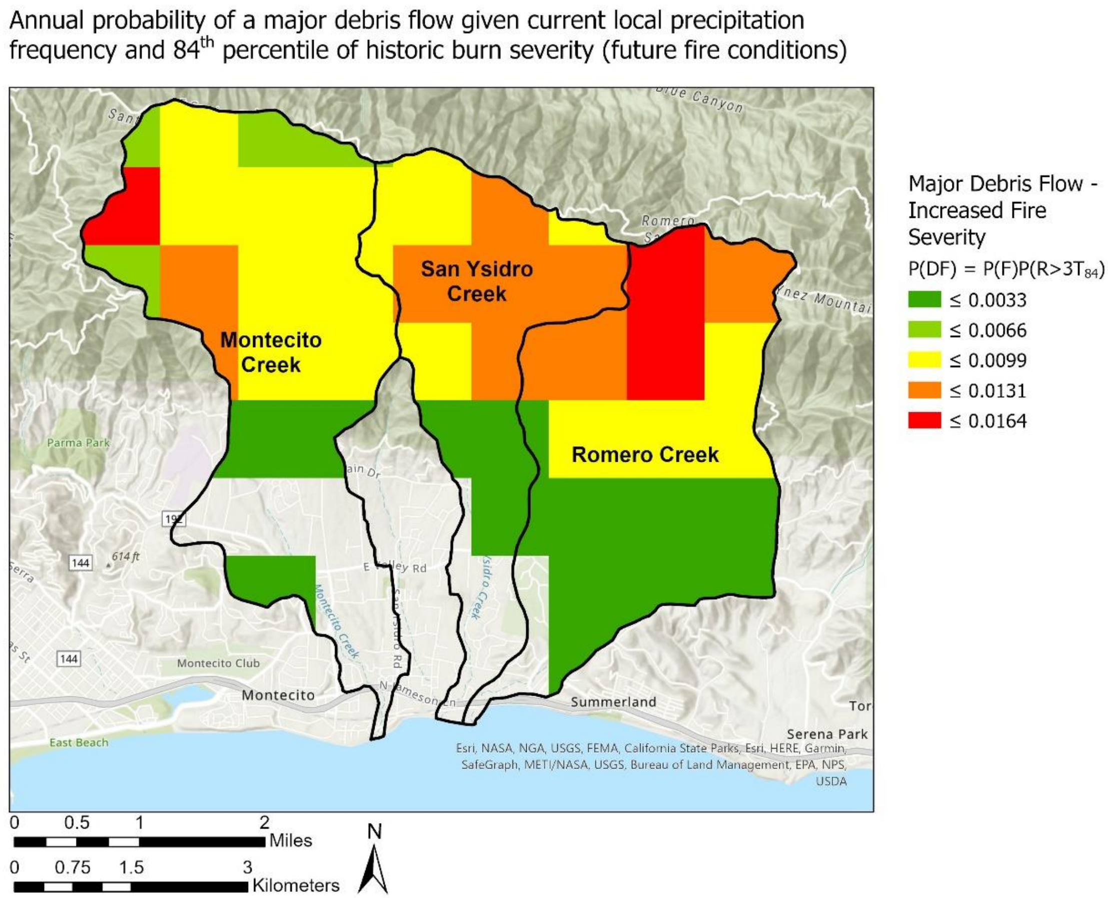

Figure 4.5 - The probability of major debris flow, $P(DF) = P(F)P(R > 3T_{84})$, within the study watersheds given current local precipitation frequency and 84th percentile of historic burn severity. *Note: The visual color scale for major debris flow likelihood is based on equal interval classification using minimum and maximum values across the three watersheds. The scale varies between the climate conditions (i.e., current, future fire, and future precipitation intensity).*

We show the estimated minimum, maximum, and mean probabilities for a debris flow and a *major* debris flow for higher burn severity, as well as the range of values for $P(F)$, T_{84}, and $3T_{84}$ for each watershed individually within the appendix.

Debris Flow Probability – Future Precipitation Conditions (Higher Rainfall Intensity)

Finally, we compared the results of the previous scenarios to the results using a projected future precipitation regime. Kean & Staley (2021) calculated these results separately from an increase in fire severity and used the rainfall intensity thresholds associated with median fire severity (T_{50}, and $3T_{50}$). This projection uses a climate scenario with an 18 percent increase in precipitation intensity by the late century (2050-2099), given the CalAdapt summary of the South Coast climate region under RCP4.5 emissions trajectory. The CalAdapt scenario projects 2.5°C of warming by the late century, corresponding to an 18 percent increase in rainfall intensity (Kean & Staley, 2021). Table 4.5 below, shows the range of values for debris flow and *major* debris flow, and *P(F)*, T_{50}, and $3T_{50}$. The results of this analysis for all three watersheds combined are shown in Figures 4.6 and 4.7 below.

Table 4.5 - Estimated range of debris flow and major debris flow probability for the study watersheds given an 18 percent increase in local precipitation intensity and median historical burn severity.

Watersheds (Combined) – Future Precipitation (Higher Rainfall Intensity)					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** $P(F)P(1.18R > T_{50})$	**Major Debris Flow** $P(F)P(1.18R > 3T_{50})$
Min.	0	0.69	2.06	0	0
Max.	0.043	1.54	4.63	0.043	0.016
Mean	0.022	0.90	2.70	0.022	0.007
Std. Dev.	0.013	0.19	0.58	0.013	0.005

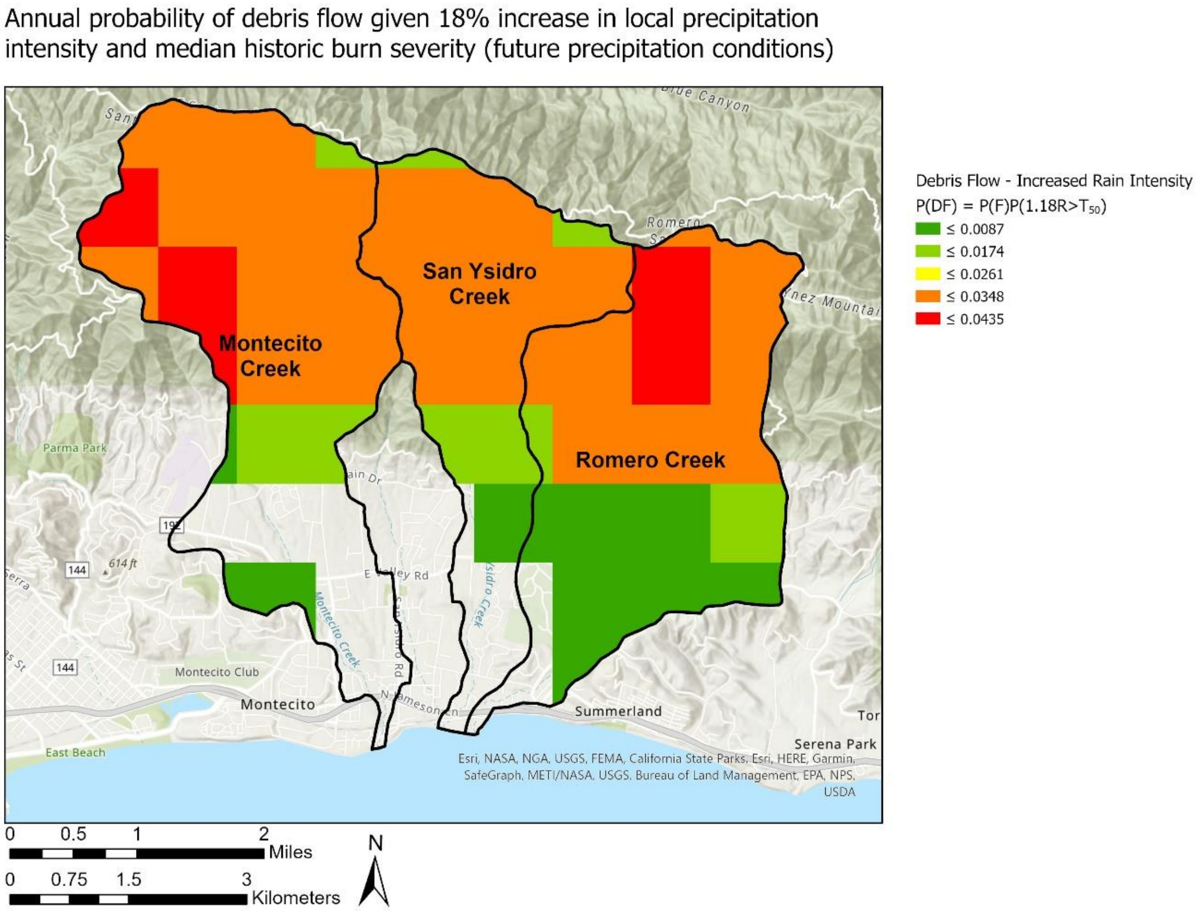

Figure 4.6 - The probability of debris flow, $P(DF) = P(F)P(1.18R > T_{50})$, within the study watersheds given an 18 percent increase in local precipitation intensity and median historic burn severity.

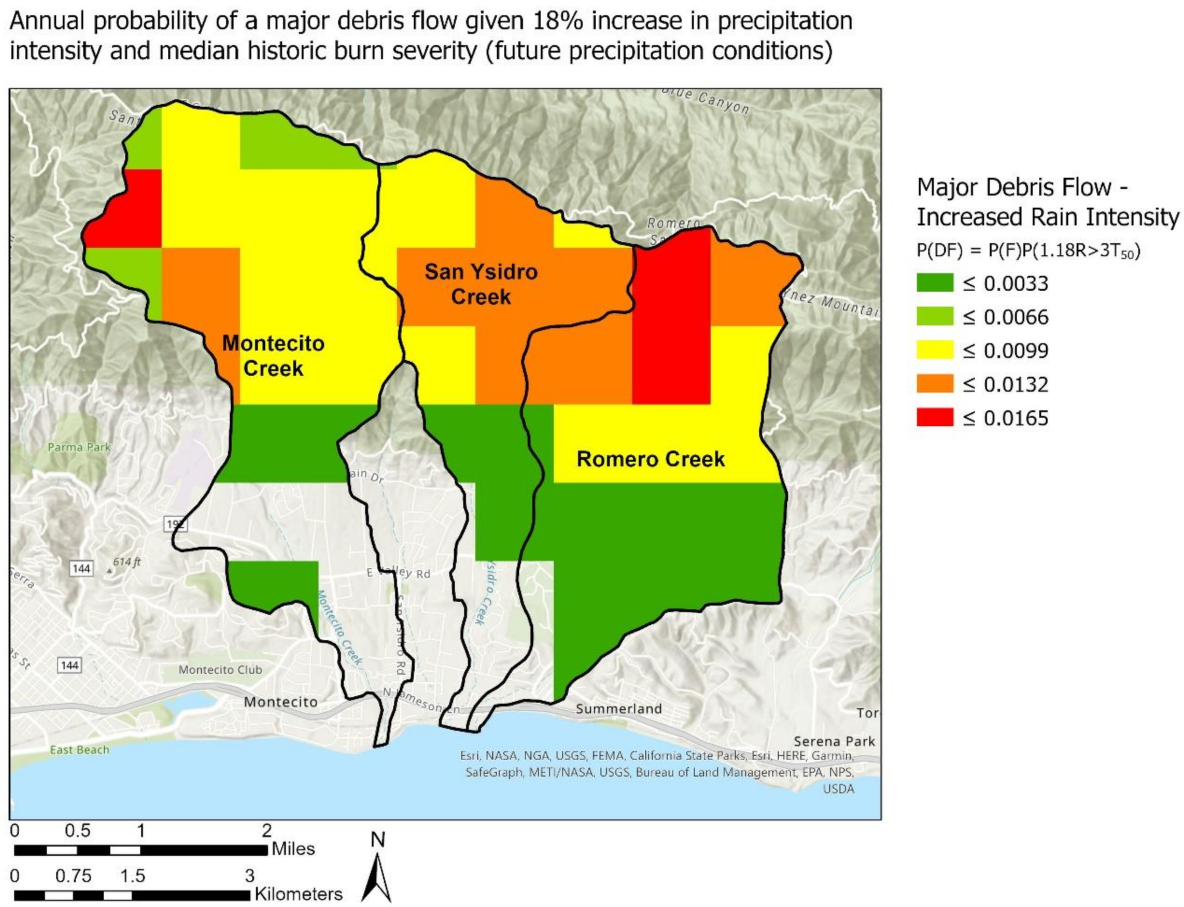

Figure 4.7 - The probability of major debris flow, $P(DF) = P(F)P(1.18R > 3T_{50})$, within the study watersheds given an 18 percent increase in local precipitation intensity and median historic burn severity. *Note: The visual color scale for major debris flow likelihood is based on equal interval classification using minimum and maximum values across the three watersheds. The scale varies between the climate conditions (i.e., current, future fire, and future precipitation intensity).*

Similar to the previous comparison between current conditions and an increase in fire severity, we see no difference in the probability of debris flow with an increase in precipitation intensity. The minimum probability is 0 percent, the maximum is approximately 4.3 percent, and the mean is 2.2 percent (SD = 1.3). As before, this similarity occurs because under current conditions, we already see a 1-year recurrence interval for a rain event with a peak 15-minute intensity exceeding the initiation threshold, T_{50}. The probability of debris flow, therefore, relies on the probability of fire, which is constant in this analysis. However, the maximum and mean probabilities of *major* debris flow are increased under increased rainfall intensity compared to current conditions (1.6 and 0.7 percent compared to 0.9 and 0.4 percent, respectively).

We show the estimated minimum, maximum, and mean probabilities for a debris flow and a *major* debris flow under an increased average rainfall intensity, as well as the range of values for *P(F)*, T_{50}, and $3T_{50}$ for each watershed individually within the appendix.

Debris Flow Volume

Using the Gartner et al. (2014) equation, we obtained sediment volume estimates for the three study watersheds delineated to their associated debris basins for post-fire debris flow events under various precipitation conditions. First, we used a baseline 15-minute peak precipitation intensity of 0.866 in/hr to be consistent with the precipitation intensity that was considered the amalgamated debris flow initiation threshold for the three watersheds in the Kean & Staley (2021) study. To model a potential climate change scenario, we calculated volumes for each watershed with a 1.02 in/hr. 15-minute precipitation intensity to incorporate an 18 percent increase in regional precipitation intensity. The 18 percent increase in precipitation intensity is projected by the RCP 4.5 emissions trajectory and is associated with a 2.5°C of warming by the late century (2050-2099) (Kean & Staley, 2021). Finally, we used a 15-minute rainfall intensity of 1.57 in/hr. as a proxy for the January 9th, 2018 debris flow event. This metric was included to show a comparison to a "worst case" scenario that occurred under current climate conditions, adding perspective to the other estimates. The volumes (yd^3) are displayed in Table 4.6.

Table 4.6 - Volume estimates (yd^3) for each watershed at 0.866, 1.02, and 1.57in/hr 15-minute precipitation intensities and debris basin capacities (yd^3).

Precipitation Intensity (in/hr)	**Montecito Creek** (yd^3)	**San Ysidro Creek** (yd^3)	**Romero Creek** (yd^3)	**Combined** (yd^3)
0.866in/hr	75,000	64,000	48,000	187,000
1.02in/hr	88,000	75,000	56,000	219,000
January 9th, 2018 Event 1.57in/hr	141,000	120,000	92,000	353,000
Debris Basin Holding Capacity (yd^3)	20,000	11,000	27,000	58,000

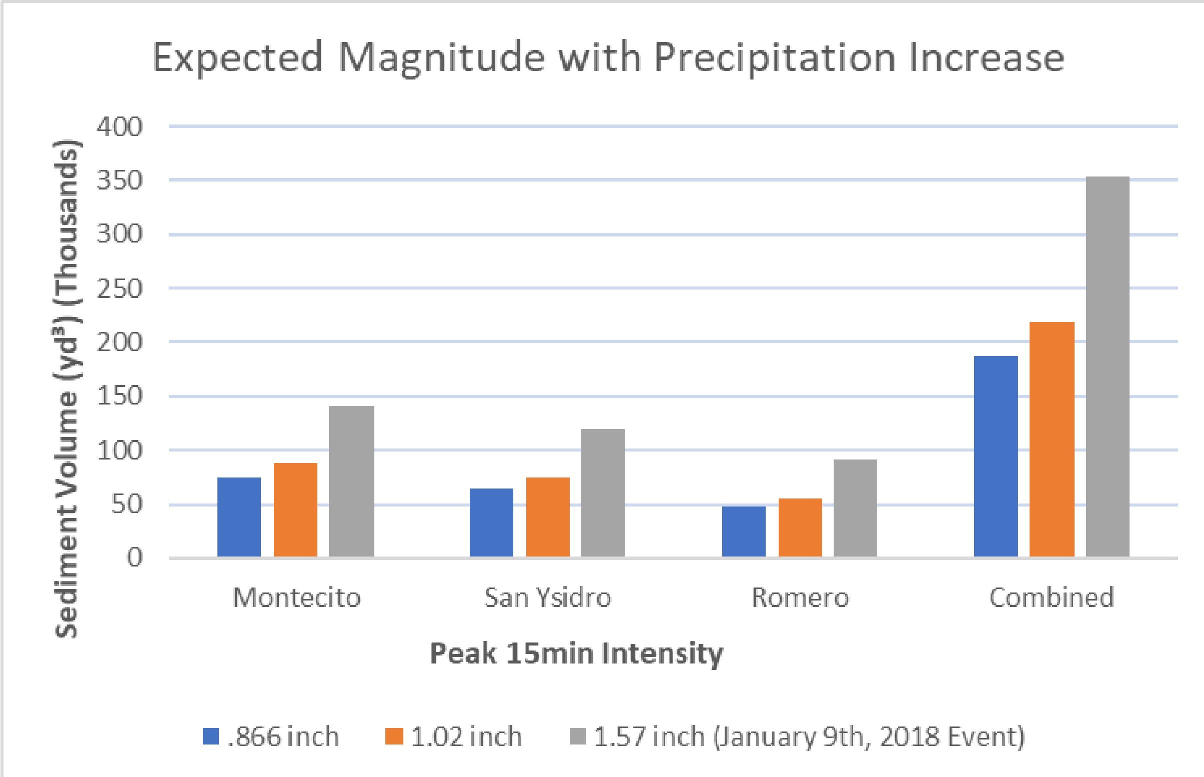

Figure 4.8 - Volume estimates (yd^3) for each watershed at 0.866, 1,02, and 1.57 in/hr precipitation intensities. For reference of capacity, Cold Springs Debris basin can hold 20,000 yd^3 and Montecito creek basin can hold 5,500 yd^3.

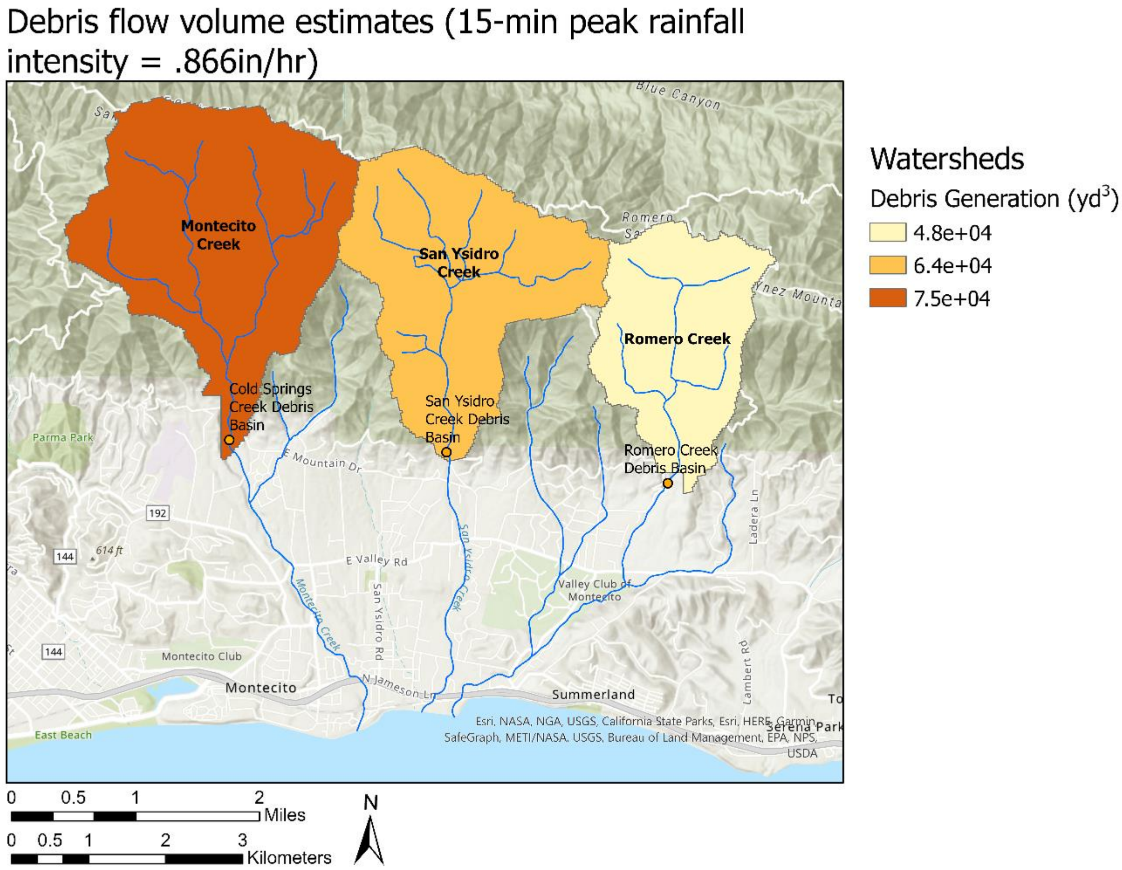

Figure 4.9 - Debris flow volume estimates for the three study watersheds using a 15-min peak rainfall intensity of 0.866 in/hr.

SECTION 5 - Cost-Benefit Analysis

Methodology

Background

Cost-benefit analysis (CBA) is a common tool used in management and business to help inform decision-makers. Applying the CBA principles to an environmental context considers the direct financial costs while incorporating the costs and benefits not captured in established market transactions. The results of a CBA can then be used to “deliberately improve the provision of the environmental service” (Atkinson & Mourato, 2008). Considering environmental and social impacts can paint a clearer picture of how certain decisions may impact different groups and aspects of the environment. Capturing the value of non-market goods and services is challenging, but new techniques and technologies have improved the sophistication of environmental CBA, improving its utility. The goal of completing a CBA for routine sediment management in the watersheds of interest is to understand and communicate the direct and indirect impacts of management choices to stakeholders.

The fundamental principles of CBA consist of adding up benefits, adding up cost, and finding the difference between the two. The results can vary depending on the steps taken in the process. The analytical framework is based on a series of sequential steps (Dobes, 2019). Nine typical steps in a CBA are:

1. Define the question, what is the analysis trying to find?
2. Determine standing, who is counted in the analysis?
3. Assess categories of impact, select impact categories of interest that can be quantified.
4. Quantify impacts, put a numerical value on the impact categories.
5. Assign monetary values to impacts, convert the impacts to a common unit of money.
6. Discount future costs and benefits, take time into account for decisions made in the present.
7. Incorporate risk and uncertainty, identify confidence intervals and areas of unknowns.
8. Assess distributional impacts, see how subgroups are affected by the proposed decision.
9. Make recommendations, incorporate all steps, and draw conclusions that will maximize benefits.

This analysis in this report attempts to address all of these steps considering data limitations and resource constraints. We decided to consider a limited framework that quantitatively addressed steps 1-6 while reserving qualitative analysis for steps 7 and 8. By limiting the scope to a few key areas, we identified important costs and benefits to be considered. By analyzing the cost-benefit relationship between impact categories, decision-makers are better informed on possible results on choices related to sediment management in the Montecito watersheds.

As part of permit requirements with the U.S. Army Corps of Engineers, SBCFCD reports routine sediment management operations in the basins, including estimates of sediment removal volumes. Using data between 2006 and 2016, we established a “status quo” scenario of sediment volumes that can be extrapolated into the future under different management strategies (table 5.1). The established “status quo” is also known as the counterfactual in the CBA field. Using the available data, we applied the CBA framework to obtain values of cost and benefits under potential management options. The three management options that the CBA considered against the counterfactual were beach nourishment at Goleta beach, market sale of sediment from the temporary storage site, and basin redesign with slotted outfalls. The management options were hypothetically modeled independent of one another, while the actual implementation can consider multiple choices.

Table 5.1 - Sediment volumes removed from 2006-2016. Note that no sediment was removed in the years not in the table. Cost data refers to the unit cost of volume and only considers market transportation cost. (Source: SBCFCD)

Debris Basin Sediment	Volume (yd^3)	Cost (USD)	Truck loads
2007 All Basins	25	$2,750	2.5
2010 Cold Springs	2,000	$220,000	200
2010 Mission	1,000	$110,000	100
2011 Cold Springs	2,000	$220,000	200
2011 Mission Creek	1,000	$110,000	100
2011 Rattlesnake	750	$82,500	75
2011 San Antonio	1,500	$165,000	150
2011 San Roque	1,700	$187,000	170
2012 Montecito Fishway	15	$1,650	1.5
Total 2007-2012	9,990	$1,098,900	999

The analysis question is, “which sediment management decision has the largest net benefit?” The standing of a CBA is defined simply as, “whose costs and benefits are being counted?” (Dobes, 2019). This analysis has given cost standing to the population of Santa Barbara County since SBCFCD has the responsibility of managing most of the routine sediment and is funded at the county level.

The categories of impact chosen for this analysis are transportation (greenhouse gas emissions, local pollutants), beach nourishment (recreation value), ecosystem services (trout habitat), and direct market cost (sediment price and trucking cost). The categories considered in this study are of interest to stakeholders because they are directly linked to possible management strategies. This analysis did not consider traffic delays from transportation, job opportunities, loss of work from debris flow, property risk from debris flow, insurance claim burden, aesthetic value, basin maintenance, among an almost unending plethora of other possible categories and indicators.

Using the data obtained from SBCFCD routine maintenance reports and the metrics of potential debris flow magnitude from Section 4 of this report, we modeled three different management scenarios and their respective public benefit to Santa Barbara County. Valuation of the impacts were assigned using studies found in the literature and other commonly available sources. We looked for settings that were most analogous to our watersheds to get the best estimates.

Using the net present value, we accounted for the opportunity cost of money and scaled it to the desired time frame of 10 years. Due to significant data gaps and complexity of the real-world components, it is difficult to precisely measure the error in this analysis. We recommend pursuing localized robust data of these impact categories to decrease error in future analysis. Finally, using all the listed factors, we developed conclusions and recommendations for decision-makers. The distributional effects were not quantitatively examined in the analysis but will be considered in the discussion.

Slotted Outfall Redesign

Costs for this scenario are based on the Gobernador Debris Basin Modification Project completed in 2009. The cost of redesign and implementation of the project was $1,776,900 (CA Natural Resources Agency, 2010). This cost was adjusted for inflation using the consumer price index data from the Bureau of Labor Statistics and multiplied by 3 to estimate the design's implementation in all three watersheds.

Benefits were calculated by using recreational values of trout fishing established in the Rhodes, Northeastern Cape of South Africa using a travel cost analysis. The paper found that 124 mi of trout fishing produced an annual value of $2,250,000 (du Preez and Hosking, 2007). This value was adjusted for inflation and divided by the length of fishing streams to obtain the value per distance of habitat of $25,000/mile annually. We then analyzed the data to obtain a value for perennial streams in our study watersheds above the debris basins of 8.2 mi across the three watersheds (USGS). By multiplying the value per distance habitat by the distance of perennial streams across the watersheds, the total annual value is $205,000.

Using the Present Value formula, the annual benefit was calculated over a 10-year period. We used a discount rate of 3 percent to consider the opportunity cost of money every year (Figure 5.1).

The present value of the habitat over 10 years is $1,756,000. The present value is then subtracted from the capital expense of the project, resulting in a net present value of -$5,129,000 over 10 years.

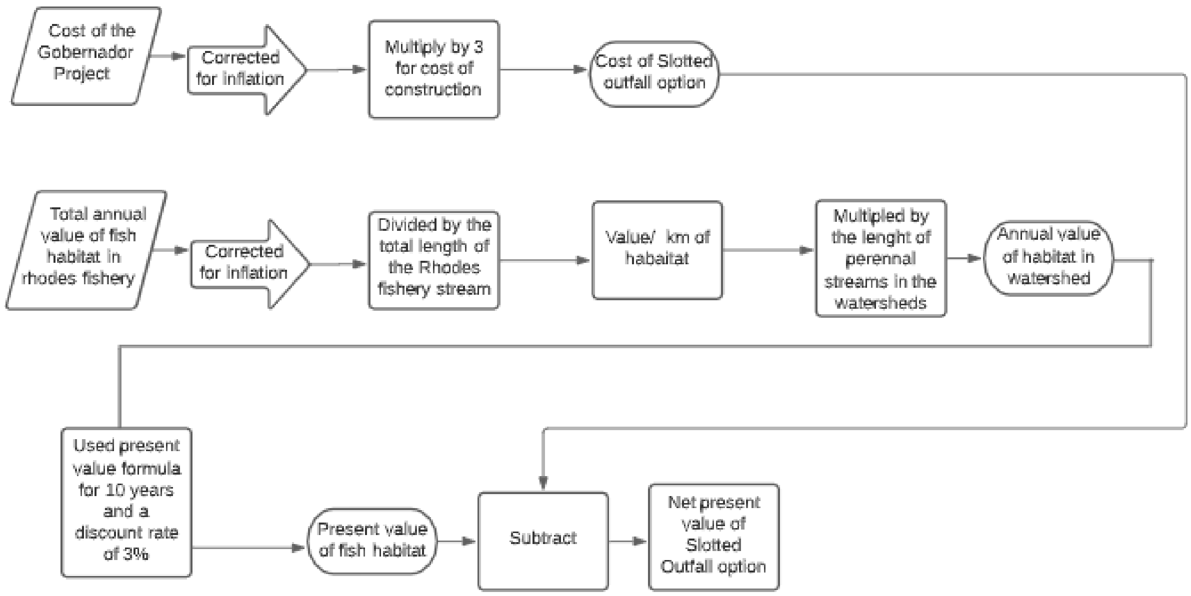

Figure 5.1 - Diagram of Cost-Benefit Analysis steps of a slotted outfall design.

Carbon Dioxide (CO_2) Pollution Cost per Mile

From debris basin operation photographs, we used the Peterbilt Model 567 10 yd^3 truck as our model transport vehicle. The Peterbilt Model 567 gets 5.8 miles (mi) per one gallon (gal) of diesel (fuelly.com). One gallon of diesel produces 22.38 lbs of CO_2 in the atmosphere (US Energy Information Administration, 2014). Multiplying the miles/ gal of the Model 567 by the CO_2 production per gallon to get 3.9 lbs CO_2/mi. Using a social cost of carbon (SCC) of ~$38/ton ($42/ metric ton) which was calculated in 2007 and used a discount rate of 3 percent (EPA, 2013). This value is adjusted for inflation and converted from metric tons to lbs. The SCC/ lb is multiplied by lb CO_2/mi to get a SCC/mi of roughly $0.10/mi (Figure 5.2).

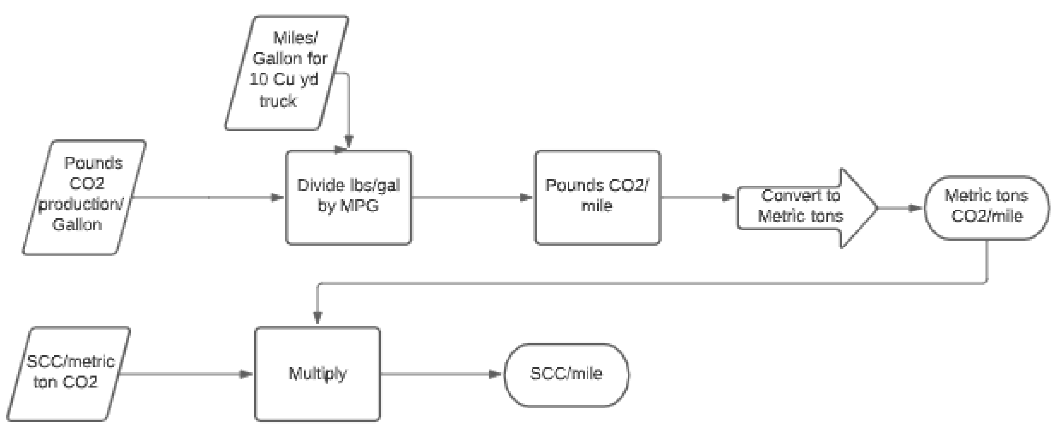

Figure 5.2 - Diagram of Cost-Benefit Analysis steps for CO_2 cost per mile.

PM 2.5 Cost per Mile

The average concentration of PM 2.5 in Santa Barbara is 8.8 **μ**g/m^3 using data from 2001-2019 (Population Reference Bureau). A diesel engine with a particulate filter can produce 250 **μ**g/km^3 (Petrovic, 2008). To find the risk of premature death caused by PM 2.5 in CA, we divided the average number of premature deaths in CA by the population of the State. As of 2016, the average number of premature deaths in CA was about 5,400 (uncertainty range of 4,200 – 6,700) (CA Air Resources Board, 2016). The population of CA was approximately 39,170,000 in 2016 (US Census Bureau). Dividing the premature deaths by the population produces a risk of 1.4×10^{-2} percent. This risk is divided by the baseline PM 2.5 concentration to get a risk percent per concentration.

By adding the diesel engine concentration to the average ambient concentration, we calculated the risk of premature death from trucking to an individual to be 4.1×10^{-10} percent. This value is then multiplied by the Value of Statistical Life (VSL) to get the cost of this risk to an individual. According to Pan et al. (2019), the VSL is $10,555,556. The density of Santa Barbara County was calculated to be roughly 118 individuals per mile, resulting in a per mile health cost of PM 2.5 of $0.0012 cent per mile (Figure 5.3).

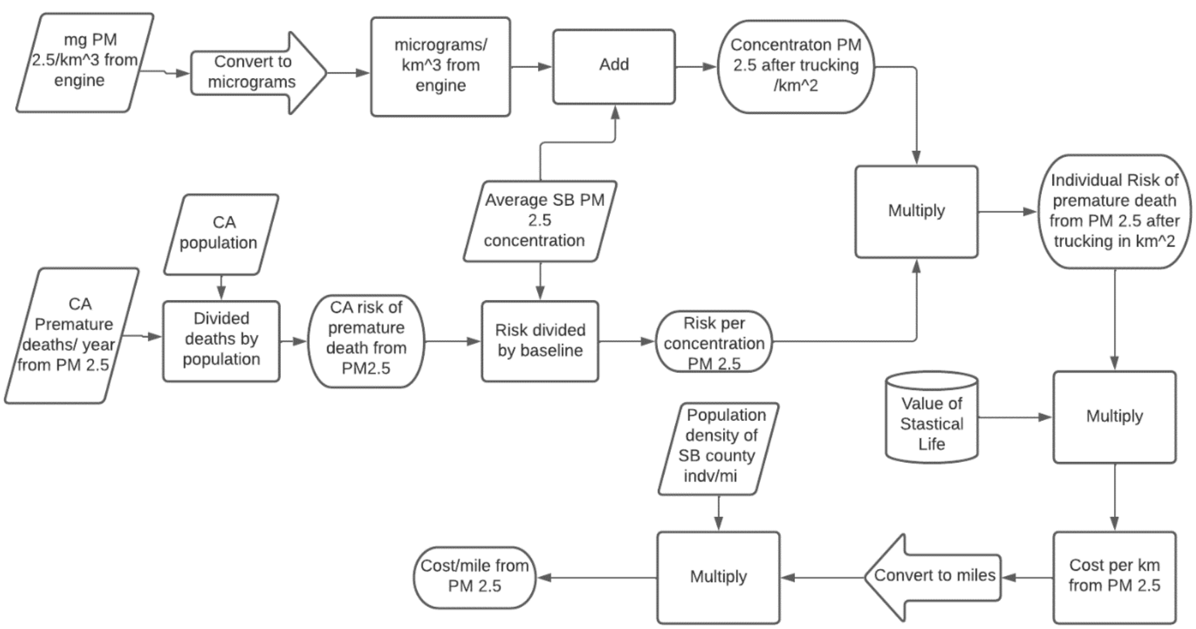

Figure 5.3 - Diagram of Cost-Benefit Analysis steps for transportation cost per mile.

The cost of both the CO_2 and PM 2.5 per mile are added and multiplied by the miles of the trip between each debris basin and the temporary storage facility or Goleta beach. This value is multiplied by 2, assuming each trip to the destination requires a return trip. $1,100 is added to this cost, understanding that the 10 yd^3 trucks are contracted for $110/ yd^3. The contracted trucking cost is the largest cost in our transportation analysis (Figure 5.4).

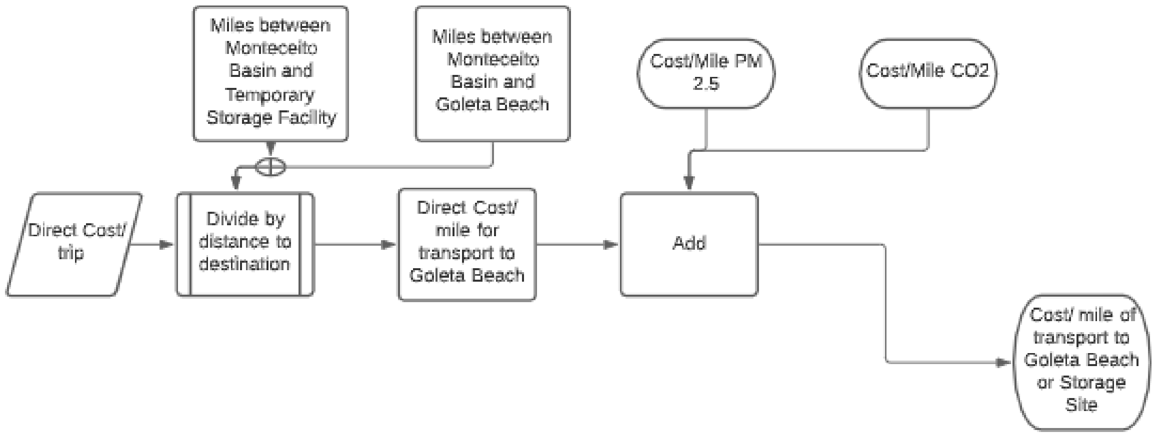

Figure 5.4 - Diagram of Cost-Benefit Analysis steps for total cost per mile.

Beach Nourishment Cost-Benefit Analysis

Under NOAA, the National Beach Nourishment Database publishes volumes of beach nourishment projects across the county. Goleta Beach has listed six projects totaling 129,000 yd^3 from 2003 to 2017 (NOAA, 2021). We divided the total amount of sediment delivered by the period to get a volume/ year value of 9,221 yd^3/year. Using google earth imaging, we constructed a polygon to calculate the area and width of Goleta beach. Using the width, we establish the linear feet of Goleta beach to be 87 feet. Considering the linear feet of Goleta beach and the average sediment input a year, we assume a steady state system of sand into sand out and calculate that 106 yd^3 of sediment are needed for 1 linear foot of beach each year.

The present value of 1 linear foot of Goleta Beach is $3,337, adjusted to $4,246 for 2021 USD using the Bureau of Labor Statistics consumer price index (BEACON, 2009). The value of sediment is roughly $39 per yd^3. The amount of sediment transported to the beach from the 3 study watersheds is estimated using the observed values from SBCFCD debris removal reports. Only the Montecito watershed has observed historical data, while relevant data from the San Ysidro and Romero watersheds is lacking.

The observed totals from the Montecito watershed (Table 5.1) are 4015 yd^3 over the ten-year time frame. Montecito Creek's observed totals were then multiplied by the percent difference of San Ysidro and Romero, respectively. The modeled sediment located in section 4 of this report for the San Ysidro watershed was 15 percent less than Montecito's modeled total, yielding about 3,400 yd^3 for the San Ysidro watershed. The modeled sediment total for Romero Canyon is 36 percent less than Montecito's modeled total from Section 4 of this report, yielding about 2,600 yd^3 from the Romero watershed (Figure 5.5). The total predicted sediment delivery over 10 years is about 10,000 yd^3. The total sediment has an estimated value of just over $300,000, while the cost of transportation to Goleta beach is roughly $1.1 million, resulting in an expenditure of just over $700,000 (Figure 5.6)

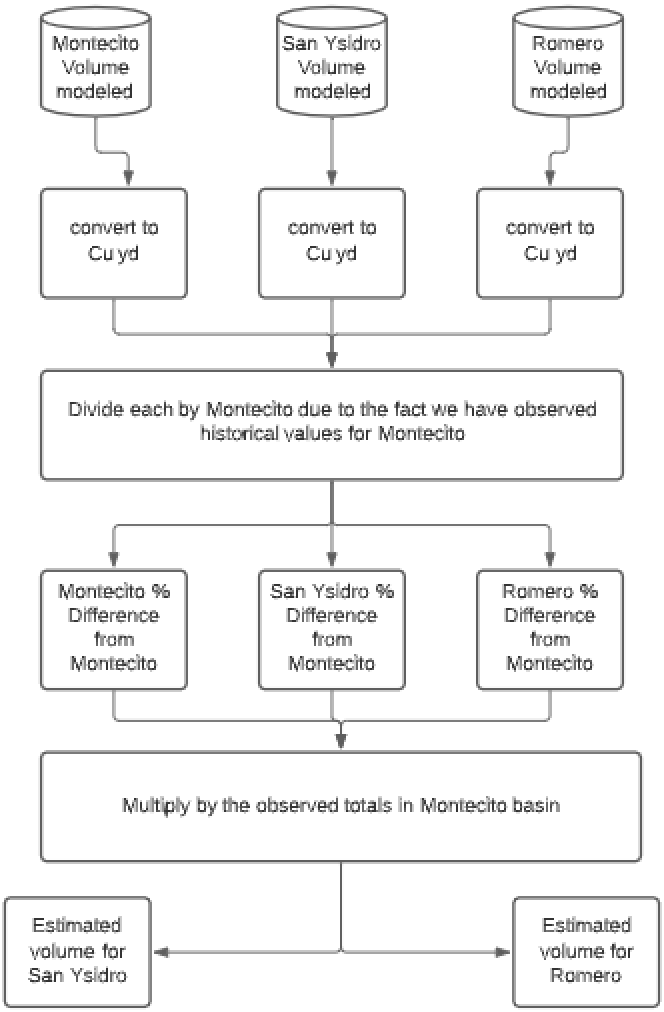

Figure 5.5 - Diagram of Cost-Benefit Analysis steps for volume estimates of each basin.

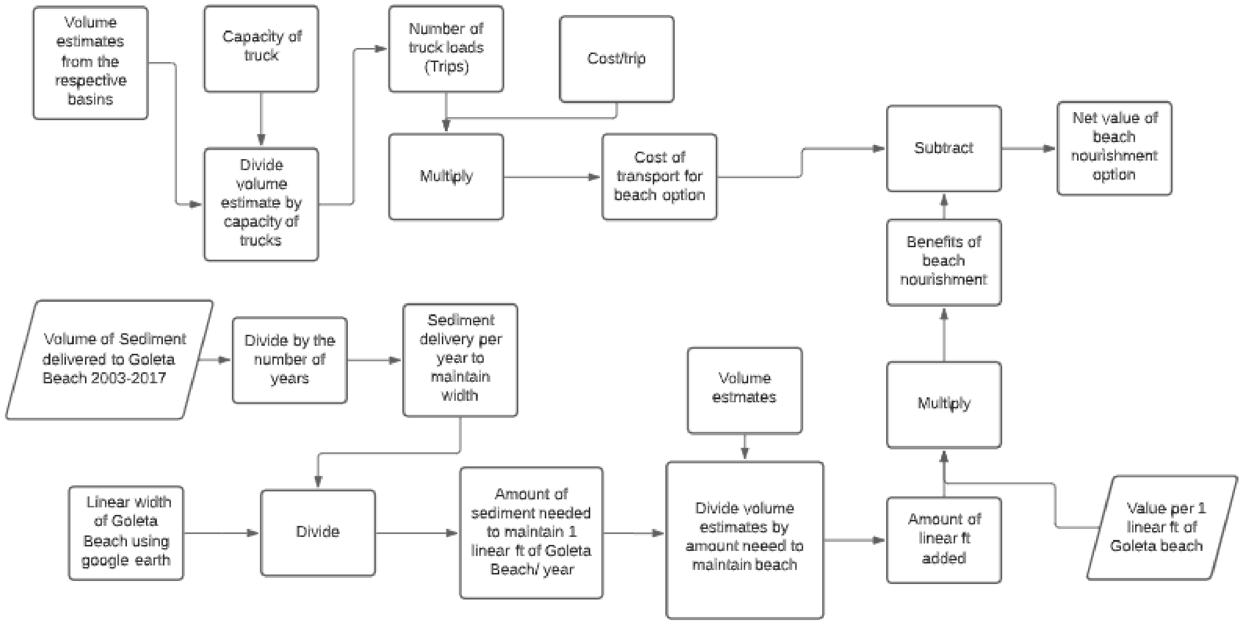

Figure 5.6 - Diagram of Cost-Benefit Analysis steps for beach nourishment.

Market Sale Cost-Benefit Analysis

The cost was calculated in the same manner for beach nourishment while adjusting the destination from Goleta beach to the temporary storage facility located off Calle Real in Santa Barbara. The total transportation cost of sediment from the respective debris basin to the storage facility is $1.1 million. The value of beach sand is $80 per ton (Earthstonerock.com), which translates to about $106 per yd^3. After the sale of the roughly 10,000 yd^3 of transported sediment over 10 years, the benefit is just under $1.1 million, leading to a net loss of $34,000.

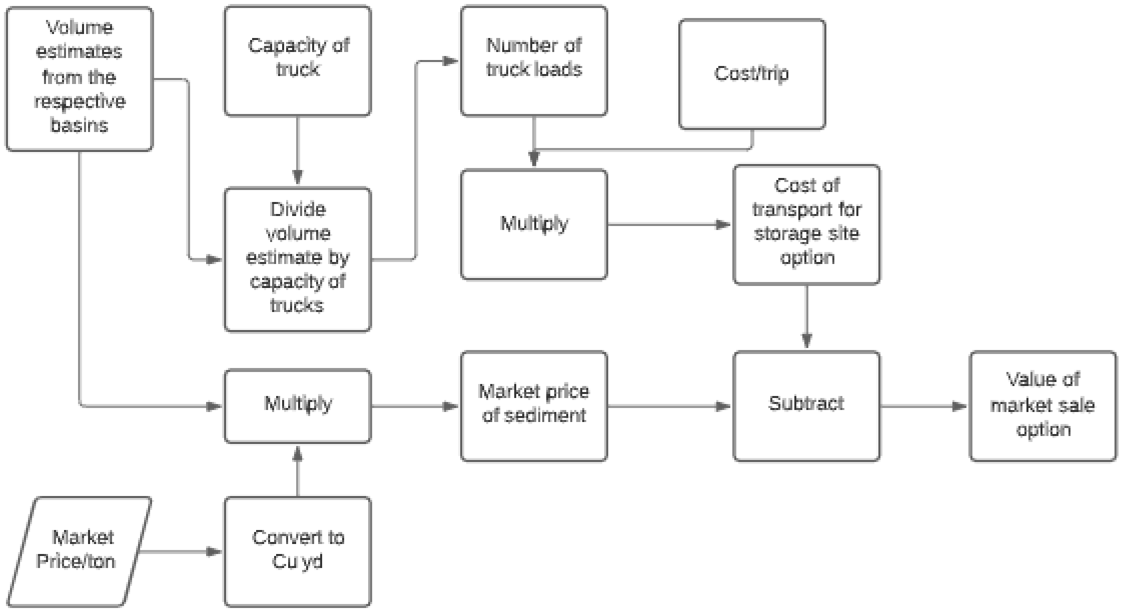

Figure 5.7 - Diagram of Cost-Benefit Analysis steps for market sale of debris.

Results

Ten Year Valuation

The results of the CBA indicate that over the next 10 years, all management plans will result in an expenditure to the county (Table 5.2). The upfront capital cost of all three basin re-designs remains the largest cost for the three options after ten years (Figure 5.8). The avoided cost of transportation varies depending on the destination, but both destinations are an order of magnitude less than the cost of the initial installation (Figure 5.9).

Slotted outfalls allow sediment to remain in the system, which reduces the undercutting of stream banks. The value added by this benefit is difficult to calculate, but further research can be conducted to determine the localized risk to property in the riparian buffer zone or the recreational value of the banks themselves.

Table 5.2 - The three-management options result in a negative net benefit to the county over 10 years.

Project	Cost	Benefit	Net Benefit
Slotted Outfall	($6,880,000)	$1,760,000	($5,120,000)
Beach Nourishment	($1,100,000)	$400,000	($700,000)
Direct Market Sale	($1,100,000)	$1,070,000	($30,000)

The expenses of Beach Nourishment from transportation are almost 3 times greater than the benefits. The methods for calculating beach benefit are described above and assume an erosion rate of over 9,000 yd^3 per year. High erosion rates, which result in the loss of beach sediments, counteract the investment of beach nourishment. The sustained effort to maintain the linear foot width of the beach requires more cost than the sediment can provide. Erosion will only intensify with increased sea-level rise, making the beach nourishment option less feasible as climate change continues to influence ocean temperatures.

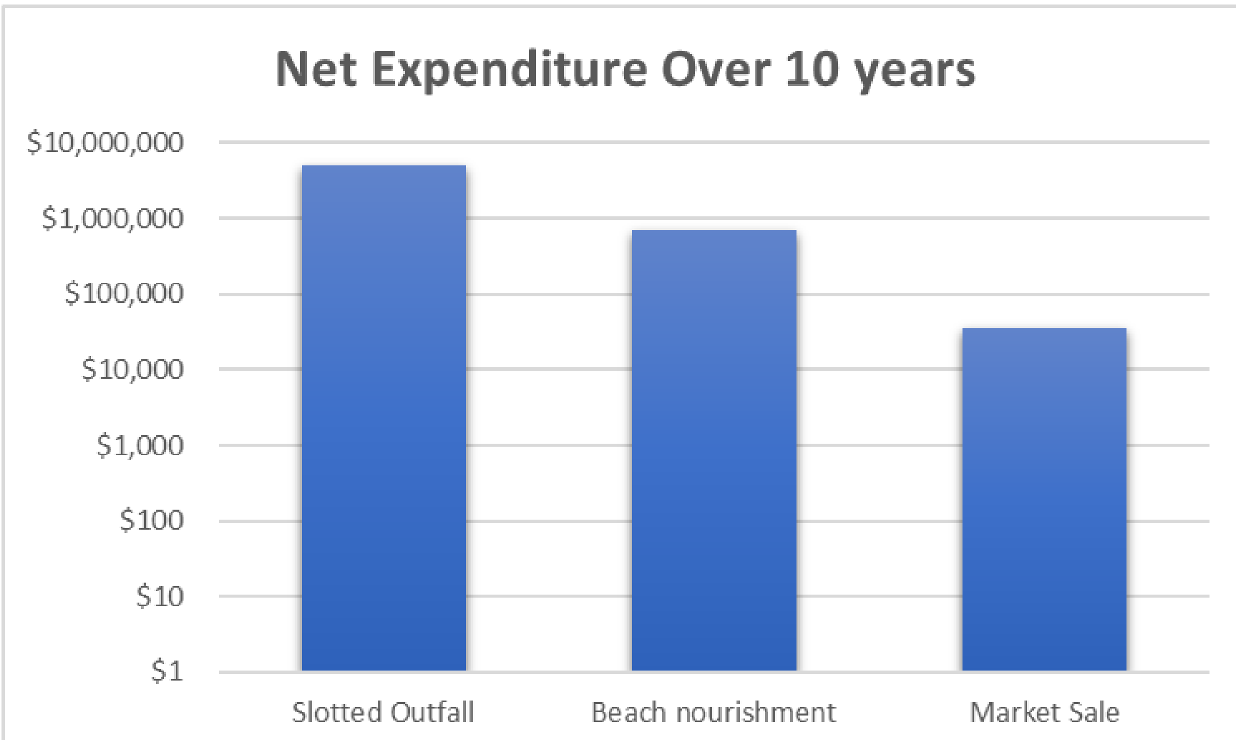

Figure 5.8 - Expenditure required for each option over a 10-year period. The Y-axis is on a logarithmic scale.

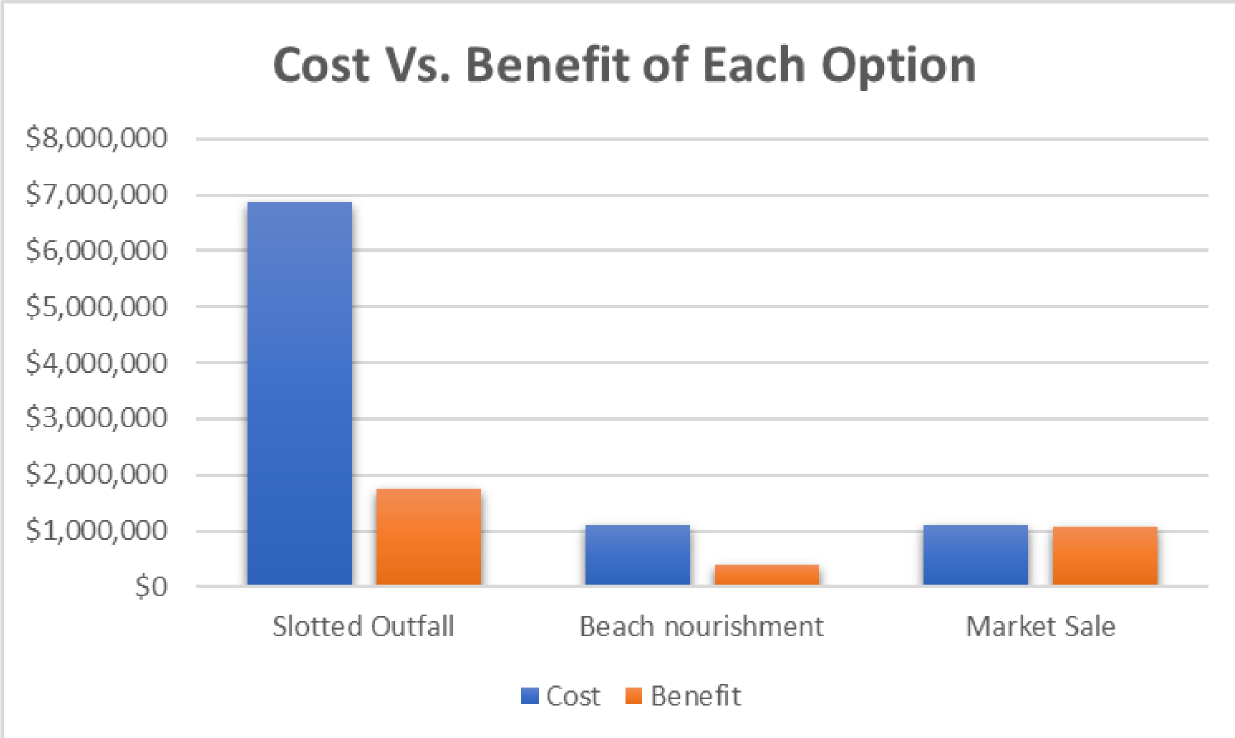

Figure 5.9 - Shows the difference between the cost and benefits over 10 years.

The slotted outfall option assumes that expenditures are fixed costs requiring no further investments into the future, while increased cost of transportation for beach nourishment and direct market sales will continue to be a factor into the future. The direct market sale has the smallest difference between cost and benefit over 10 years. It should be noted that there are likely to be additional costs of sorting the sediment removed from the debris basins to different sizes for the direct sale option. These were not included in the analysis. In reality, the additional steps in processing will only increase the cost of the option, thus decreasing the net benefit.

Each management option's cost is divided by the population of Santa Barbara County, resulting in $11.49 for the slotted outfall option, $1.58 for beach nourishment option, and $0.08 for the market sale option (Figure 5.10).

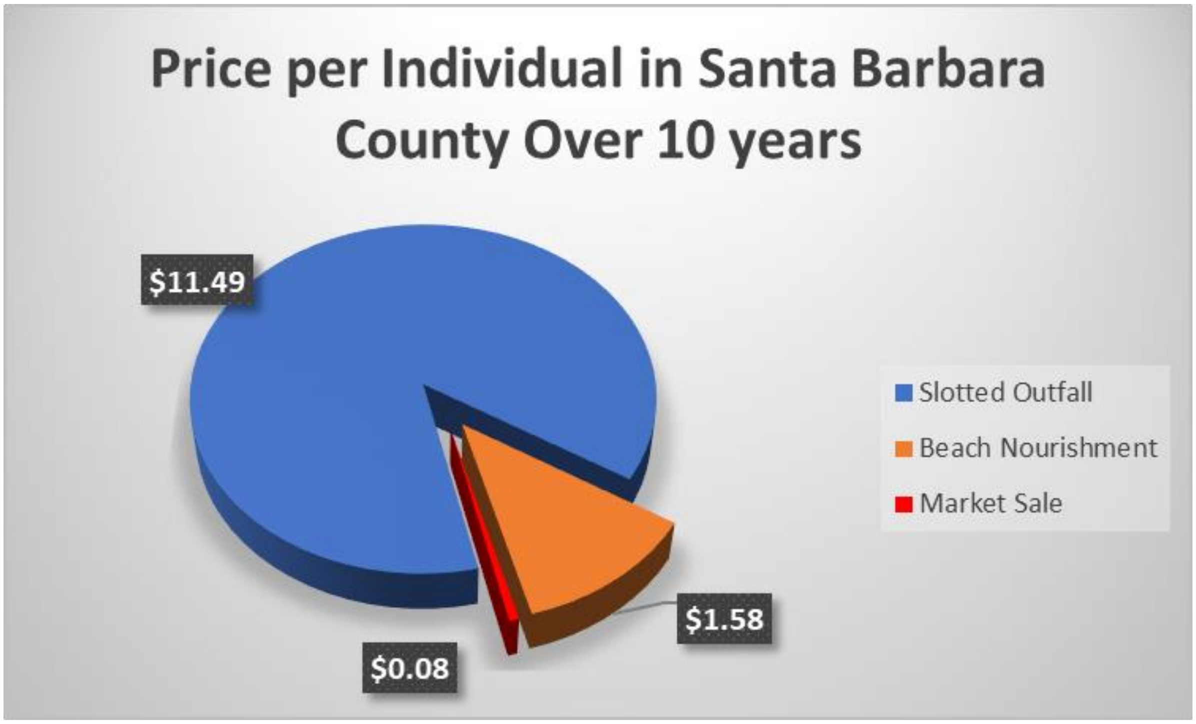

Figure 5.10 - The slotted outfall option has a larger per person cost than the other options.

100-Year Valuation

To forecast future costs and benefits for the 10-year time period, we multiplied the cost and benefits by factors of ten and calculated the net benefit. Assumptions are that there is no change in cost of transportation or benefits from each option. When our analysis is extrapolated 100 years into the future, we see that the slotted outfall redesign maximizes the benefit for the County.

The Slotted outfall assumes benefits from trout habitat from the first year. It is important to note that improved trout habitat does not guarantee the presence of trout in the streams and the potential benefits analyzed here will not be realized until recreational fishing is supported in the streams. This is a relatively unlikely scenario in the given time frame considering the listed status of steelhead in the region. Regardless, the slotted outfall option decreased expenditure by a factor of 13 while the beach nourishment increased expenditure by a factor of 100 (Figure 5.11).

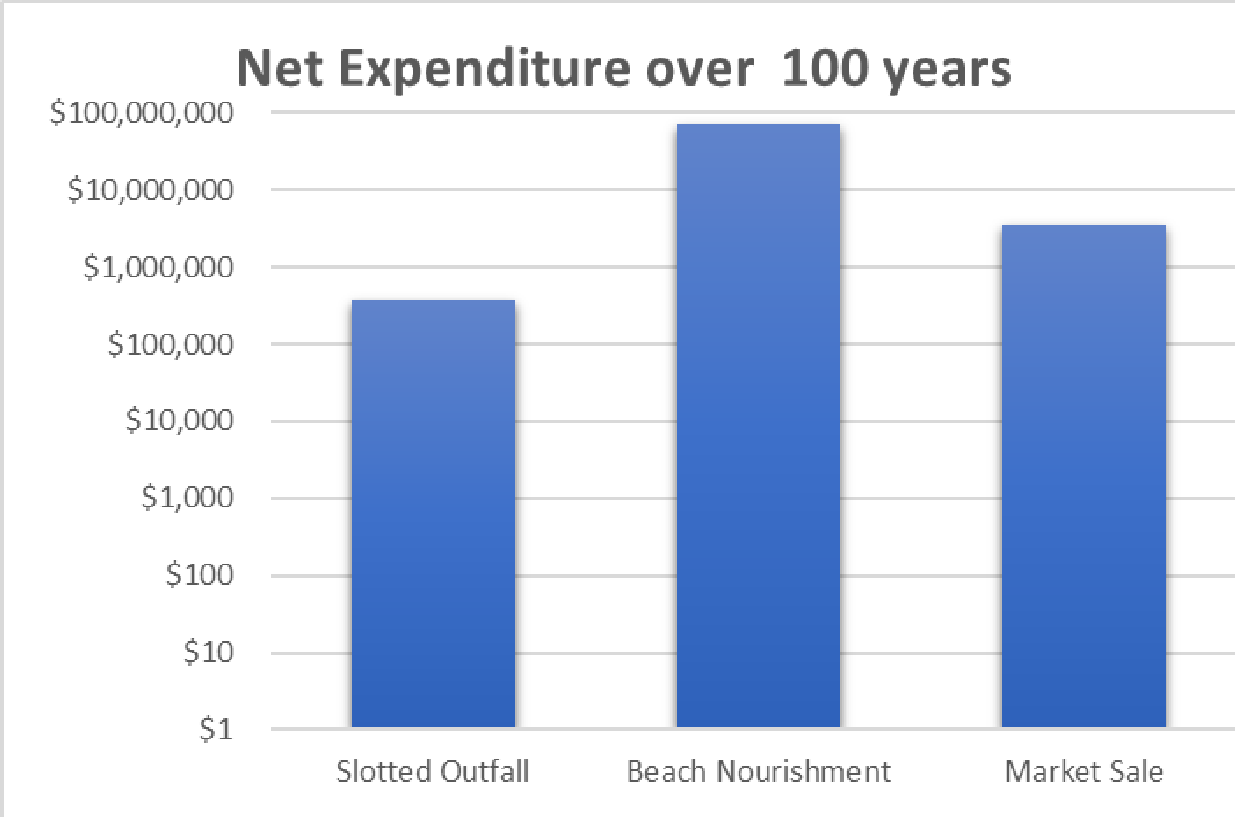

Figure 5.11 - Beach Nourishment has the largest expenditure over a 100-year time frame.

Each 100-year extrapolation of management option costs per individual resulted in ~$160 for beach nourishment, $8.07 for market sale and $0.85 for the slotted outfall (Figure 5.12).

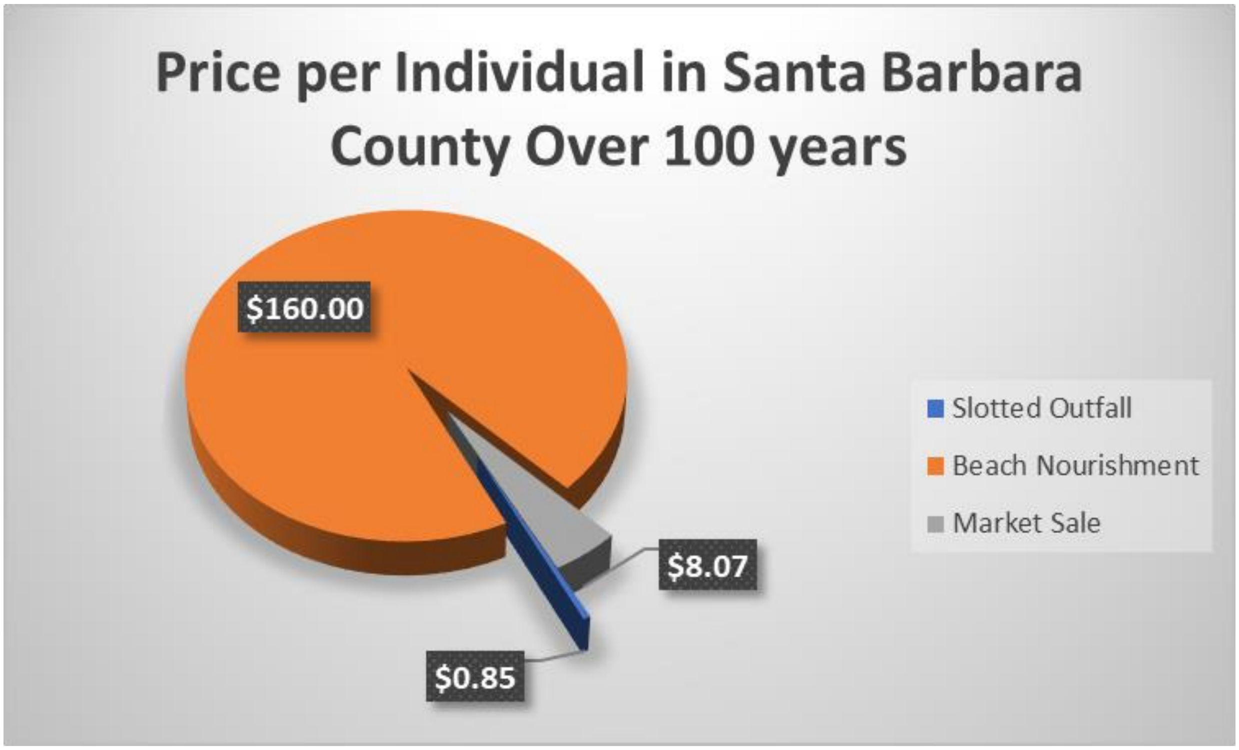

Figure 5.12 - Beach Nourishment has the biggest per capita cost over a 100-year time frame.

The results of the transportation costs analysis indicate that the contracted cost of sediment transportation is the largest. Pollution contributes much less to the overall cost with CO_2 being about \$0.10 per mile and PM 2.5 being \$0.0012 cents per mile (Figure 5.13). CO_2 uses a global consideration of its effects and PM 2.5 is localized to those within half a mile of the trucking route. Note that there are other pollutants from diesel engine exhaust that could have been evaluated but were not included within the scope of this analysis.

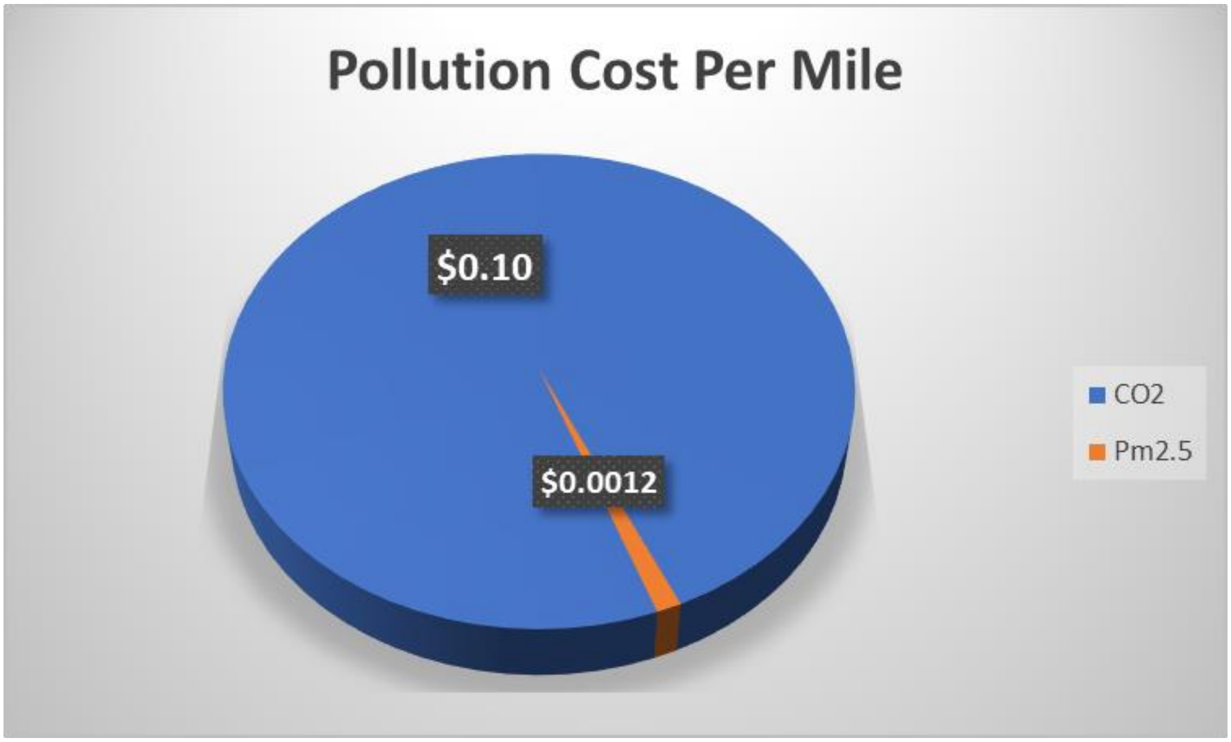

Figure 5.13 - The majority of pollution impact cost comes from CO_2 emissions.

SECTION 6 - Discussion

Shifts to Fire Cycle

As discussed previously in this report, sediment transport is strongly correlated with wildfires. The relationship between wildfires and climate change is an area of active research. Since 1979, California has experienced ∼1 °C increase in autumn temperature, ∼30 percent decrease in autumn precipitation, and a 20 percent increase in fire indices (Goss et al., 2020). Climate change is one of the suspected drivers behind the change in the wildfire regime in California. Research suggests that while fire occurrence in the study watersheds is driven more by human activity, climate change has more of an impact on fire intensity (Syphard, et al., 2017).

Several compounding factors are tied to higher occurrence and severity of wildfires in California. Overall, the factors are mostly related to reduced fuel moisture from increased evaporative demand, reduced snowpack, and reduced warm-season precipitation frequency (Williams et al., 2019). Regardless of the extent to which any one of these factors is tied to change in the fire regime, the pattern is evident. The annual burned area across California has increased by 405 percent between 1972 and 2018 (Williams et al., 2019). While our analysis generally treats the fire regime as constant, with fires ignitions being mostly anthropogenically-dominated, a warming climate will likely result in a longer, more intense fire season. Coupled with an increase in the likelihood for precipitation to initiate the transport of sediments, there may be a potential increase in debris flow recurrence or magnitude with an increase of fire occurrence or intensity.

Precipitation Intensity Changes

Precipitation is an essential driver of post-fire debris flow events. Even if a landscape has been burned to bare soil in a wildfire event, a debris flow is only likely to occur with enough rainfall over a short duration leading to an exceedance of an initiation threshold. Managers and scientists are most concerned with both initiation thresholds at which rainfall results in a debris flow and future precipitation intensity shifts resulting from climate change. A better understanding of initiation thresholds and climate drivers can inform landslide hazard assessments and community evacuation decisions in advance of forecasted precipitation in post-wildfire watershed conditions (Oakley, 2021).

As shown by empirical evidence and modeling, even a typical storm with a yearly recurrence interval can initiate a debris flow. Rainfall intensity is the primary driver rather than rainfall total (Kean personal communication, 2021). For post-fire debris flow events, a high 5- to 15-minute peak intensity is a better predictor of debris flow initiation than the hourly or total storm precipitation totals. If the recurrence intervals for high-intensity rain events shift with climate change, there will likely be consequences for sediment management and increased hazard from post-fire debris flow.

With climate change, there is evidence of a global and regional shift towards increased precipitation intensity (Papalexiou & Montanari, 2019). Hourly precipitation extremes may intensify as global temperatures increase, following the Clausius-Claperyon relationship that links air temperature and atmospheric humidity (Ali et al., 2021). An increase in temperature results in a greater amount of moisture held in the atmosphere. From a regional perspective, precipitation intensity in southern California could increase hazard from high magnitude debris flows, particularly when coupled with possible shifts in the recurrence and intensity of fire.

Generally, infrastructure design and rainfall-triggered hazard models rely on static hydroclimatic extremes, although climate change is rendering these existing assumptions increasingly outdated. Climate model simulations for California's Fourth Climate Change Assessment utilized under RCP8.5 project that the frequency of a fifty-year precipitation event could double in southern California, leading to rain events that are more intense and twice as frequent. Meanwhile, the average annual mean precipitation total will not change substantially (AghaKouchak et al., 2018). Effectively, the current fifty-year event would become a twenty-five-year event.

Uncertainty

California's Fourth Climate Change Assessment report models future climate change and assesses potential impacts across the state by using general circulation models (GCMs). The public has access to these GCMs through a state portal called Cal-Adapt, which utilizes 32 GCMs. On Cal-Adapt, the user can reduce the analysis down to 10 GCMs or downscale variables to particular regions within the state, including the Central Coast. Of the GCMs used in the Cal-Adapt analyses, four models are identified as priority models for temperature and precipitation changes: HadGEM2-ES (Warm/Dry future climate in CA), CNRM-CM5 (Cool/Wet future climate in CA), CanESM2 (Average climate future in CA), and MIROC5 (Complementary to other models) (Cal-Adapt, 2022).

In addition to GCMs that model climate, future emission scenarios are vital to consider when modeling projected climate change. The Fourth Assessment and Cal-Adapt model climate change under Representative Concentration Pathway (RCP) 4.5 or 8.5. RCP4.5 is an emissions trajectory where emissions peak around 2040 and then decline, whereas RCP8.5 sees emissions rise strongly through 2050 and plateau in 2100.

Kean & Staley (2021) modeled debris flow recurrence under precipitation changes under RCP4.5. Future precipitation changes under RCP8.5 are more severe and could result in more sediment transport. A source of uncertainty regarding climate change's future influence on debris flow is the degree to which emissions will continue to occur into the future. The RCPs attempt to capture these future trajectories, but are largely dependent upon a range of predictions regarding politics, economics, and social factors that are beyond the scope and scale of this project.

Modeling Results

The models used in the project give a rough estimate of the probability of post-fire debris flow and major debris flow, as well as sediment volumes that would need to be transported away from debris basins under various rainfall intensities. The results of these models provide a useful generalization of the likelihood and potential magnitude of post-fire debris flows in the region. They also provide information about the extent to which debris flow likelihood and magnitude in the region are sensitive to various impacts of climate change, such as an increase in precipitation intensity and fire severity.

Using the Kean & Staley (2021) model, we found that the non-major post-fire debris flow likelihood is not sensitive to an increase in fire severity and precipitation intensity. The probability of debris flow in the region does not increase with an increase in fire severity or precipitation intensity. Under current conditions, there is already a 1-year recurrence interval for a rainfall event with a 15-minute rainfall intensity exceeding the initiation thresholds for post-fire debris flow in the watersheds (i.e., the likelihood for exceedance of the initiation threshold is roughly 100 percent in a given year under current conditions). Thus, neither decreasing the initiation threshold by increasing fire severity or increasing rainfall intensity by 18 percent under the RCP4.5 late century conditions changes the likelihood of non-major post-fire debris flow.

Given the equation, $P(DF) = P(F \cap R>T)$, and the fact that $P(R>T)$ is equal to 1 for the watershed cells with a non-zero probability of debris flow, the likelihoods of non-major post-fire debris flow in the study watersheds rely solely on the likelihood of a fire occurring in the watersheds. The model assumes that future fire likelihood does not rely on antecedent conditions or past fire because the chaparral vegetation of the watersheds is fire-adapted (Keeley, 2000) and the ecosystems are ignition-limited (Keeley & Syphard, 2017). The model generally treats the likelihood of fire as constant and lacks the ability to predict change to the fire regime into the future, such as with an increase in the length or severity of "fire weather" or hot and dry conditions in the Southern California region. A study by Mann et al. (2016) stresses the importance of incorporating a multitude of anthropogenic and natural factors in models to predict future wildfire recurrence. Future research regarding change in fire regimes due to climate change would likely improve the results of the climate change prediction analysis of this model.

On the other hand, the Kean & Staley (2021) model did indicate sensitivity of major post-fire debris flow likelihood to both an increase in fire severity and an increase in precipitation intensity within the study watersheds. The results indicate that an increase in precipitation intensity and higher burn severity will lead to increased likelihood of major debris flow occurrence when compared to the current conditions scenario that uses local precipitation frequency and median of historical burn severity. The model showed that for an increase in either fire severity or precipitation intensity, the mean annual probability for a major debris flow in all three watersheds combined increases from 0.4 percent to 0.7 percent, with the maximum annual probabilities increasing from 0.9 to 1.6 percent.

The results of this analysis demonstrate that climate change impacts, specifically an increase in fire severity and precipitation intensity, could lead to increased recurrence of major debris flows in the three study watersheds. However, these impacts were examined independently of each other, without consideration of a future increase in fire recurrence. Further research that examines the complex relationships and feedback between the multitude of factors related to climate change would improve modeling results. A more in-depth look at the role of each of these variables on debris flow probability should be investigated to better understand how to best prepare in the context of a changing climate.

The estimated magnitudes of post-fire debris flow in the study watersheds using the Gartner et al. (2014) model show an increase in sediment volume with an increase in precipitation intensity. For example, in the Montecito Creek watershed under current conditions, which uses the minimum 15-minute precipitation intensity associated with a debris flow (0.866 in/hr), the model shows the potential magnitude of 75,000 yd^3 of material delivered to the Cold Springs debris basin. Under an 18 percent increase in precipitation intensity proposed by the RCP4.5 emissions trajectory scenario for the late century, we see volume increased to 88,000 yd^3 of material, roughly a 17 percent increase. As the recurrence interval for larger storm events decreases, the potential in the watersheds for larger post-fire debris flow events increases if there is a fire.

Site-specific empirical or mechanistic models can provide useful metrics of hazard and potential magnitude. However, more advanced models rely on the multi-layered factors like hillslope, soil conditions, vegetation health, and meteorological predictions. Without accurate and precise measurements, the results are affected by wide margins of error. To reduce this margin of error, obtaining data for the watersheds is needed over significant periods of time to observe relationships between these factors with confidence. Ideally, this would occur on a site-specific basis with precise instrumentation and scientific methodology. More advanced models may be able to predict sediment yield more accurately, although collecting data needed to calibrate them will always be a challenge due to the low frequency of very large storm events in this region. We recommend the most beneficial investment is the ability to collect higher-resolution rainfall data in the watersheds, considering the elevation and spatial differences between the rain gauges that currently exist. The data interpolation of rainfall is a source of error and can be decreased with finer resolution of rain gauges up the watershed, particularly in the undeveloped reaches.

Habitat and Ecosystem Services

Efforts should be made to promote ecosystem health and restore habitat as much as possible to maximize public benefit. Endangered species, like the steelhead trout, which used to be abundant in the region, are now threatened with extinction. Hard infrastructure, like the traditional debris basins found in watersheds across the state can lead to loss of stream habitat for endangered species. Organizations like NMFS and SBCFCD have worked collaboratively to incorporate biological sustainability into management of sediment. This project recognizes a huge opportunity for sustainable value and co-benefits to be generated from maintenance of healthy fishery habitat. The loss of a species' genetic lineage is an irreversible cost which cannot be recovered. Little research has been done to monetarily account for the benefits provided by the steelhead trout. The species has uncalculated cultural value, particularly connected to the native Chumash and there is an inherent value that stakeholders make considerable investments to preserve. For example, SCHR has put substantial funding and effort into cultivating a sustainable future for the species through habitat restoration.

Valuing Sediment

Managers should continue to advance the perception of sediment as a benefit and conduct a more detailed analysis of sediment markets. Our market research found that an analogous material to watershed sediment sold for around $80/ton and resulted in a net negative value. The analysis also found that at a hypothetical price of around $85/ton breaks even with the cost of transports and results in a net positive. However, our analysis did not account for the labor associated with the onsite activities or the costs of transactions, which will undoubtedly increase the overall cost. Using the results of this analysis, we suggest further research of the costs and market opportunity of sediment in this form.

Another recommendation for further research is examining the use of sediments for beach nourishment. This analysis found that the costs associated with beach nourishment (i.e., transportation) resulted in a relatively lower expenditure to the county of Santa Barbara. However, further analysis should account for the costs of onsite activities, the potential impairments to water quality, better estimates of erosion rates for particular beaches, and more detailed beach valuation, which were not examined. More accurate data in these areas can be leveraged to maximize the benefit provided by beach nourishment projects. Further utilizing the work done in the coastal sediment management space by the Beach Erosion Authority for Clean Oceans and Nourishment (BEACON), a joint powers authority in Santa Barbara and Ventura Counties, is recommended. BEACON has expertise in programmatic permitting regarding beach disposal of sediments, and harnessing this expertise could alleviate the regulatory burdens inherent in beach nourishment permitting. It should be noted that beach nourishment may be uniquely susceptible to sea-level rise and climate change compared to the other management options.

Beach Nourishment and Sea Level Rise

The two major causes of global sea level rise are thermal expansion caused by warming of the ocean and increased melting of land-based ice like glaciers and ice sheets (NOAA, 2021). Sea level rise has started having an impact on most coastal communities across the globe and will continue to increase into the foreseeable future (Hall et al., 2019). The consensus in the literature is that sea level rise will continue to progress, but the magnitude of its progression is highly uncertain (Lempert et al., 2007). This uncertainty leaves coastal managers with the responsibility to plan for a new dynamic and complicated system. There is a body of literature treating coastlines as human-natural coupled systems, emphasizing the need for a focus on beach nourishment and other erosion adaptation strategies (Cutler et al., 2020). Beach nourishment is not intended to be a permanent solution to erosion but it can allow for planned redeposits of sediments as erosion continues over time (Landry, 2011).

Sea level is estimated to rise between 1.2 ft - 1.7 ft by 2050 (Sweet et al. 2022). As the sea level rises, erosion is assumed to decrease beach width and increase hazard, necessitating investment in adaptation strategies like further beach nourishment (Cutler et al. 2020). Hard infrastructure such as sea walls can help protect the coastline and retain benefits of investment for longer periods compared to beach nourishment projects. However, this type of sea level rise mitigation strategy amplifies negative effects on ecosystems, especially on the sensitive estuary environments like Goleta slough located near Goleta beach.

Infrastructure Improvements

Infrastructure improvements to debris basins exemplify one type of adaptation strategy to climate change that is already being implemented in the county. The debris basin on Gobernador Creek, which was modified with a slotted outfall design in 2008 to facilitate fish passage, still maintains flood control capability. It performed well during the January 9th, 2018 major debris flow. Large boulders settled upstream of the debris basin, while fine sediments passed through the structure (SBCFCD, 2021). This contrasts with the box outfall structures on Montecito, San Ysidro, and Romero Creeks, which were filled to capacity by sediments and debris, then overtopped with catastrophic impacts (Lancaster et al., 2021).

With a projected increase of precipitation intensity due to climate change, the county's planned installation of slotted outfalls to other debris basins in the study area (Cold Springs, San Ysidro, and Romero Creeks) is a major move towards infrastructure adaptation to climate change. All the study area debris basins were designed and constructed in the 1960s and 1970s when climate change was not a management consideration. As shown by the January 9th, 2018 debris flow, the debris basins are not capable of handling the magnitude of sediment generated by a major event.

Even during minor or moderate events, entrained sediments have unintended consequences in the economic sphere (sediment transport and disposal costs) and the environmental sphere (impeded fish passage, disconnected sediment transport). The planned modification to a slotted outfall at the Cold Springs, San Ysidro, and Romero debris basins will make these important installations more resilient to projected impacts from climate change, improve fish passage, and decrease sediment management costs.

Beyond modification of existing infrastructure, investment and installation of new infrastructure is an important management consideration to account for hazard from climate change. A debris basin on Buena Vista Creek is planned for construction in 2023. Seventy-five percent of the funding for the $4 million project has been procured from the FEMA Hazard Mitigation Grant Program (SBCOEM, 2022).

Randall Road Debris Basin

The new Randall Road Debris Basin, which expands the riparian corridor along San Ysidro Creek and provides an area for debris flow runout to settle, is effectively complete. At the time of writing, SBCFCD is finalizing the acquisition of the final parcel required for the project. The Randall Road area was particularly impacted by the January 9th, 2018 debris flow, and by a previous debris flow in 1969 (Kean et al., 2019; SBCFCD, 1969). SBCFCD's acquisition of parcels on Randall Road ensures homes will not be rebuilt in a recurrent hazard zone and provides benefits to downstream residents by reducing hazard from debris flow.

Planning and Climate Resilience

The Climate Change Vulnerability Assessment (CCVA), conducted by the County of Santa Barbara Planning and Development Department, identifies and analyzes community vulnerability to potential stressors and hazards from climate change. The CCVA identifies debris flow as a *secondary* climate hazard due to the fact that it is influenced by the *primary* climate stressors of temperature and precipitation. The CCVA informs Santa Barbara County's Climate Action Plans, which is scheduled for adoption in 2023. The CCVA and Climate Action Plan are Planning and Development's primary climate resiliency related activities, although general zoning and regulation can also help cultivate resiliency by minimizing development in hazard zones when and where feasible.

The Santa Barbara County Office of Emergency Management (OEM) is finalizing the updated 2022 Multi-Jurisdictional Hazard Mitigation Plan (MJHMP). The MJHMP describes SBCFCD's Debris Control Program. This includes routine maintenance to ensure a 15-foot-wide pilot channel, and long-term maintenance with proscribed sediment removal after design capacity has been reduced by 25 percent or following a wildfire in the watershed. The Debris Control Program covers management activities on the study area creeks and scheduled modifications to Cold Springs, San Ysidro, and Romero debris basins. SBCFCD activities are identified as the first line of defense to mitigate hazard from debris flow, while the MJHMP provides detailed assessment of potential hazards.

Hazard types in the MJHMP are screened and scored based on several factors: frequency or probability of occurrence (1-Unlikely to 4-Highly Likely), geographic extent (1-Limited to 3-Extensive), potential magnitude/severity (1-Negligible to 3-Critical), and overall significance (1-Low to 3-High). Mudflow & Debris Flow received a 4 for frequency/probability of occurrence (highly likely), a 1 for geographic extent (limited), a 3 for potential magnitude/severity (critical), and a 2 for overall significance (medium). The total score for debris flow was 10/15—three additional points were granted based on public input and ranking by the Mitigation Advisory Committee.

The hazard assessment also offers further details regarding the history, probability, geographic extent, and climate change considerations of debris flow in Santa Barbara County and examines mitigation planning. The MJHMP identifies vulnerability primarily in the footprint of the January 9th, 2018 Montecito debris flow and further identifies goals and objectives in the context of mitigation actions. These mitigation options are evaluated using the STAPLEE methodology developed by FEMA. STAPLEE encompasses social, technical, administrative, political, legal, economic, and environmental criteria to evaluate a mitigation action. A score of ten or greater is considered high and the Sediment Management Program is ranked with a score of 12.

The MJHMP prioritizes the development of a Sediment Management Plan and a permitted disposal program for sediments coordinated with BEACON to ensure both resiliency to future debris flows and environmental benefits for beach nourishment and fish passage. Additional elements of the Sediment Management Plan include identifying watersheds in the county that could benefit from debris management, the acquisition of potential stockpile site(s) for storage and sorting of sediments for future beneficial reuse, and the collaboration between OEM, SBCFCD, and BEACON to enact and fund an effective Sediment Management Program. The MJHMP further identifies the debris basins modifications discussed in this report as individual actions to mitigate debris flow hazards.

Ongoing adaptation efforts at the municipal level, including the County of Santa Barbara through CCVA and MJHMP, can identify and mitigate climate change magnification of debris flow hazard. It is also important that municipalities engage with the public during the planning and implementation process. Santa Barbara County, through partnerships with non-governmental organizations and the wider public, can achieve management outcomes which minimize hazards, mitigate climate change, and attain broader societal benefits. A few of these organizations are detailed below:

The Partnership for Resilient Communities

The Partnership for Resilient Communities (TPRC) was founded following the January 9th, 2018 Montecito debris flow. TPRC's focus is on community safety and resiliency in support of and in coordination with public agency efforts in Santa Barbara County. TPRC's primary achievement has been the installation of six ringnets on the Montecito, San Ysidro, and Romero Creek watersheds. While the ringnets cannot capture smaller sediments, they are able to partially entrap and slow larger debris such as woody vegetation or boulders.

Santa Barbara Bucket Brigade

The Santa Barbara Bucket Brigade (SB3) formed as a community volunteer response to the January 9th, 2018 debris flow which deeply affected the community of Montecito. SB3 was created to help the community prepare and respond to natural disasters and community crises through volunteer training, coordination, and deployment. Since its inception, SB3 has led upward of 3,000 volunteers within the community to help those directly affected by the debris flow. This includes efforts such as, digging mud and debris out of homes, helping families find lost belongings, cleaning up public open spaces, helping to restore local trails and walking paths, and rescuing endangered oak trees.

SECTION 7 - Recommendations

Sediment Management Options

In constructing our recommendations for sediment management approaches, we emphasized long-term sustainability. The options that we considered to best meet this criterion were those that accounted for healthy ecosystems and incorporated climate change adaptations into the overall approach or design.

The continued implementation of slotted outfalls in the debris basins has the greatest potential to maximize benefits for the County of Santa Barbara, while also improving ecosystem health and accounting for climate change impacts on future debris flows. The potential of slotted outfalls to (1) improve trout habitat, (2) avoid costs associated with transportation or storage of sediments, and (3) increase infrastructure resiliency towards climate change, leads us to recommend implementing slotted outfall designs to debris basins.

The next best option is using established earth material markets to sell the sediment. While this option allows for increased revenue streams, costs associated with transportation, storage, and sorting contributes to overall expenditure. Nonetheless, from our CBA, we found that this option has the smallest cost to benefit ratio. An additional consideration is that this approach has an adverse effect on the effort to mitigate climate change due to the carbon emissions associated with transportation.

As a final, least-beneficial option, we recommend using beach nourishment as a sediment management approach. The fact that we recommend this option last is largely due to continued costs associated with trucking to beach locations. Also, beach erosion rates counteract the longevity of the investment of sediments to beach areas. The informal "80:20" rule is another potential barrier to the beach nourishment option. The 80:20 rule regulates that the ratio of sediment size be no more than 20 percent fines for beach nourishment purposes and is applied by the California Coastal Commission. The rule stems from 40 CFR –Part 227, Section 227.13 (b)(1) (U.S. Code of Federal Regulations), which intends to limit deposition of fine sediments on beaches. Fine sediments are more susceptible to absorbing chemical contaminants that adversely impact marine environments and human health (Li, 2020). This and other regulatory aspects make the utilization of sediments for beach nourishment more onerous. This option would also require state permitting, which often comes with tricky time-lines that inhibit flexibility. An option to counteract this obstacle is what is called a "Programmatic Permit." Partnering with BEACON for this alternative is recommended, although the acquisition of a programmatic permit for sediment disposal is challenging as the life of the permit may not align with the needs of the sediment manager (i.e., a five-year permit may not cover a period with any appreciable accumulation of sediments that require management).

We do not believe that any of these options are necessarily mutually exclusive. Discovering opportunities for these approaches to be used in conjunction with one another can maximize the benefit for the public good, especially considering unique temporal factors that can influence important decisions. For instance, the market for earth materials can decrease dramatically following a storm event due to the increased availability of material from debris flows. Transportation costs can be reduced using more fuel-efficient vehicles. The valuation of beach areas can vary considering spatial or temporal aspects of erosion from storms and recreational patterns. We believe that finding harmony between all available options can help move sediment management in a more sustainable direction, resulting in long-term social and environmental benefits.

Additional Management Approaches

Some additional management recommendations include implementing fuel management of the watersheds by thinning of brush and other combustible materials, investing in clean energy solutions for sediment transport, and researching more efficient sediment stockpiling sites of sediment for sale (i.e., reducing distance from source to storage site). Fuels management has the potential to decrease the likelihood and severity of future wildfires, although effectiveness was not examined here and was beyond the scope of this project. Purchasing new sediment storage sites is another option for managers, although site identification and acquisition is a barrier. Establishing a processing site facilitates the establishment of markets for sediment, which would also be conducive to public-private partnerships.

Another interesting potential is using water market incentives to open new sediment stockpile sites on private land. Owners of fallowed agricultural land could be incentivized to store sediment through water market credit awards. Water markets are currently emerging around the country and could provide future solutions to water quantity issues in the state and provide co-benefits for sediment storage. Ayres et al. (2021) provides more context on the benefits of water markets for groundwater management in California.

Public Outreach

All these management options are going to be made under the scrutiny of public opinions. We recommend transparent decision-making, which includes ensuring public access to data as much as possible to proactively communicate the pros and cons of each decision. Maximizing global benefits while balancing local risk is a challenge and must be handled with care. Utilizing iterative policymaking and leveraging public forums to listen and communicate will be an important part of sediment management in watersheds. These forums can also be used to maintain saliency of major debris flows like the January 9th, 2018 event to help guide future planning efforts of the area. Community forums like the winter emergency preparedness meetings should continue to be offered to gain and disseminate valuable information. Santa Barbara County’s recently released Climate Change Vulnerability Assessment and ongoing 2022 Multi-Jurisdictional Hazard Mitigation Plan update are long-term planning processes that are important to consider in regards to debris flow hazard and sediment management.

Modeling Recommendations

Increasing model parameters to reflect complex relationships among climate change-influencing factors could improve the accuracy and precision of models in the long term.

However, we have also discussed the opportunity to improve existing models using site-specific observations and data.

In a discussion about the sources of error for their empirical debris flow magnitude model, Gartner et al. (2014) suggested that one such source might relate to the variability of the volumes of sediment removal from retention basins reported by public agencies after debris flow events. These volume records were used in the regression analysis to develop the model. Gartner et al. (2014) state that the variability may stem from inaccurate tallies of the number of trucks needed to remove debris, differences in the amount of material loaded into each truck, and different methods used by various agencies to measure sediment volumes. According to the study, the large span in the 95-percent prediction interval is partly due to error in the measurement of sediment volume from the available data (Gartner et al., 2014).

The focus of agencies like SBCFCD is to protect human livelihood, safety, and property. This supersedes other considerations, but any further collection of physical observations or data from agencies could help inform the development of models and would likely improve post-fire debris flow prediction ability. We suggest that any opportunities for collaboration between agencies and scientists studying debris flow would greatly benefit overall modeling capability.

Another question that arises when discussing the magnitude or recurrence interval of debris flow within the watersheds is to what extent does the exhaustion of erodible material from previous debris flow change the metrics of existing models? Collection of more data, such as LiDAR-derived estimations of sediment volume or watershed geomorphology, can help answer questions regarding the sediment budgets of watersheds. More research in this area can develop pre-and post-debris flow watershed characteristics that can be added as variables to further refine future modeling results and hazard assessments. An example of efforts to gather these metrics can be seen in research by Morell et al., (2021), which used LiDAR differencing and field observations to examine the origins of sediment mobilized during the 2018 Montecito debris flow. Furthermore, this study reiterated the importance of estimating the budget of stored sediment in debris flow hazard assessments (Morell et al., 2021).

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SECTION 9 – Appendix

Montecito Creek Watershed – Current Conditions

Table 9.1 - Estimated range of debris flow and major debris flow probability for Montecito Creek Watershed given current local precipitation conditions and median historical burn severity.

Montecito Creek – Current Conditions					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** $P(F) \times P(R > T_{50})$	**Major Debris Flow** $P(F) \times P(R > 3T_{50})$
Min.	0	0.77	2.31	0	0
Max.	0.043	1.45	4.35	0.043	0.007
Mean	0.025	0.91	2.74	0.025	0.004
Std. Dev.	0.013	0.19	0.58	0.013	0.002

San Ysidro Creek Watershed – Current Conditions

Table 9.2 - Estimated range of debris flow and major debris flow probability for San Ysidro Creek Watershed given current local precipitation conditions and median historical burn severity.

San Ysidro Creek – Current Conditions					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** $P(F) \times P(R > T_{50})$	**Major Debris Flow** $P(F) \times P(R > 3T_{50})$
Min.	0	0.69	2.06	0	0
Max.	0.043	0.95	2.84	0.043	0.009
Mean	0.024	0.80	2.40	0.024	0.005
Std. Dev.	0.010	0.06	0.18	0.009	0.002

Romero Creek Watershed – Current Conditions

Table 9.3 - Estimated range of debris flow and major debris flow probability for Romero Creek Watershed given current local precipitation conditions and median historical burn severity.

Romero Creek – Current Conditions					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** P(F) x P(R >T_{50})	**Major Debris Flow** P(F) x P(R >$3T_{50}$)
Min.	0	0.72	2.17	0	0
Max.	0.043	1.54	4.63	0.043	0.009
Mean	0.020	0.91	2.74	0.020	0.004
Std. Dev.	0.015	0.22	0.65	0.015	0.003

Montecito Creek Watershed – Future Fire (Higher Burn Severity)

Table 9.4 - Estimated range of debris flow and major debris flow probability Montecito Creek Watershed given local precipitation conditions and 84th percentile historical burn severity.

Montecito Creek – Future Fire (Higher Burn Severity)					
	P(F)	**T_{84}** (in/hr)	**$3T_{84}$** (in/hr)	**Debris Flow** P(F) x P(R > T_{84})	**Major Debris Flow** P(F) x P(R > $3T_{84}$)
Min.	0	0.65	1.96	0	0
Max.	0.043	1.10	3.30	0.043	0.014
Mean	0.025	0.76	2.26	0.025	0.007
Std. Dev.	0.013	0.12	0.37	0.013	0.004

San Ysidro Creek Watershed – Future Fire (Higher Burn Severity)

Table 9.5 - Estimated range of debris flow and major debris flow probability for San Ysidro Creek Watershed given local precipitation conditions and 84th percentile historical burn severity.

San Ysidro Creek – Future Fire (Higher Burn Severity)					
	P(F)	**T_{84}** (in/hr)	**$3T_{84}$** (in/hr)	**Debris Flow** $P(F) \times P(R > T_{84})$	**Major Debris Flow** $P(F) \times P(R > 3T_{84})$
Min.	0	0.59	1.78	0	0
Max.	0.043	0.78	2.35	0.043	0.016
Mean	0.024	0.68	2.03	0.024	0.009
Std. Dev.	0.010	0.04	0.13	0.009	0.004

Romero Creek Watershed – Future Fire (Higher Burn Severity)

Table 9.6 - Estimated range of debris flow and major debris flow probability for Romero Creek Watershed given local precipitation conditions and 84th percentile historical burn severity.

Romero Creek – Future Fire (Higher Burn Severity)					
	P(F)	**T_{84}** (in/hr)	**$3T_{84}$** (in/hr)	**Debris Flow** $P(F) \times P(R > T_{84})$	**Major Debris Flow** $P(F) \times P(R > 3T_{84})$
Min.	0	0.61	1.84	0	0
Max.	0.043	1.10	3.30	0.043	0.016
Mean	0.020	0.75	2.24	0.020	0.007
Std. Dev.	0.015	0.13	0.40	0.015	0.006

Montecito Creek Watershed – Future Precipitation (Higher Rainfall Intensity)

Table 9.7 - Estimated range of debris flow and major debris flow probability for Montecito Creek Watershed given an 18% increase in local precipitation intensity and median historical burn severity.

Montecito Creek – Future Precipitation (Higher Rainfall Intensity)					
	P(F)	T_{50} (in/hr)	$3T_{50}$ (in/hr)	Debris Flow $P(F)P(1.18R > T_{50})$	Major Debris Flow $P(F)P(1.18R > 3T_{50})$
Min.	0	0.77	2.31	0	0
Max.	0.043	1.45	4.35	0.043	0.014
Mean	0.025	0.91	2.74	0.025	0.007
Std. Dev.	0.013	0.19	0.58	0.013	0.004

San Ysidro Creek Watershed – Future Precipitation (Higher Rainfall Intensity)

Table 9.8 - Estimated range of debris flow and major debris flow probability for San Ysidro Creek Watershed given an 18% increase in local precipitation intensity and median historical burn severity.

San Ysidro Creek – Future Precipitation (Higher Rainfall Intensity)					
	P(F)	T_{50} (in/hr)	$3T_{50}$ (in/hr)	Debris Flow $P(F)P(1.18R > T_{50})$	Major Debris Flow $P(F)P(1.18R > 3T_{50})$
Min.	0	0.69	2.06	0	0
Max.	0.043	0.95	2.84	0.043	0.016
Mean	0.024	0.80	2.40	0.024	0.009
Std. Dev.	0.010	0.06	0.18	0.010	0.004

Romero Creek Watershed – Future Precipitation (Higher Rainfall Intensity)

Table 9.9 - Estimated range of debris flow and major debris flow probability for Romero Creek Watershed given an 18% increase in local precipitation intensity and median historical burn severity.

Romero Creek – Future Precipitation (Higher Rainfall Intensity)					
	P(F)	**T_{50}** (in/hr)	**$3T_{50}$** (in/hr)	**Debris Flow** $P(F)P(1.18R > T_{50})$	**Major Debris Flow** $P(F)P(1.18R > 3T_{50})$
Min.	0	0.72	2.17	0	0
Max.	0.043	1.54	4.63	0.043	0.016
Mean	0.020	0.91	2.74	0.020	0.007
Std. Dev.	0.015	0.22	0.65	0.015	0.006