San Diego County Hydrology Manual Technical Studies

Bulking Factor Study

October
2022

Final Report

Prepared for:

County of San Diego
Department of Public Works
Flood Control Section

Prepared by:

RIVER FOCUS

In association with:

RICK
ENGINEERING COMPANY

San Diego County Hydrology Manual Technical Studies
Bulking Factor Study

Final Report

October 2022

Prepared for

County of San Diego
Department of Public Works
Flood Control Section

In association with

RICK Engineering Company
Water Resources Division

Prepared by

River Focus, Inc.
www.riverfocus.com

Jon Viducich, PE
Senior Hydraulic Engineer

A. Jake Gusman, PE
River Focus Project Manager

REGISTERED PROFESSIONAL ENGINEER
ANDREAS JAKE GUSMAN
No. C61032
EXP. 12/31/22
CIVIL
STATE OF CALIFORNIA

This work was prepared by me or under my supervision.

Jake Gusman December 31, 2022
Signature *Expiration Date*

Cover photo: Small watershed near Barrett Lake, San Diego County, with high debris-flow occurrence probability following the 2020 Valley Fire, by Jon Viducich, River Focus.

Table of Contents

List of Tables

List of Figures

List of Appendices

1 INTRODUCTION

1.1 Study Purpose

This study was commissioned as part of a current effort to update the 2003 San Diego County Hydrology Manual ("Hydrology Manual"). A Hydrology Manual Technical Advisory Committee (TAC) was formed in 2019 to review the Hydrology Manual in its entirety and coordinate improvements to various technical sections.

Four subcommittees were formed in 2020 to address outstanding TAC comments from the ongoing review of the current Hydrology Manual procedures. One subcommittee focused generally on the topic of sediment bulking factors, identified several potential solutions to address issues identified by the TAC, and made the following recommendations to the TAC in a "Technical Memorandum (Draft)" dated December 7, 2020. A copy of the technical memorandum is included in Appendix A of this report.

Bulking Factors

- Recommend use of an "upper curve/limit" with the option to compute a watershed-specific value, if it can be defended (subject to third-party review).
- Create a map of high-risk areas to be considered for bulking factor application; map could be based on chronic problem areas, slope, vegetation, geology, etc.

Post-fire Hydrology

- Recommend including a new section with a general overview and application (not prescriptive methodology), including references of where to find additional information.

Alluvial Fans

- Do not recommend adding a separate section on alluvial fans, but instead reference County policy, etc.

The TAC requested further information and support for these recommendations. The purpose of this study is to review the sediment bulking and post-fire hydrology methodologies used by other public agencies in Southern California, along with current best practices, and to make recommendations about appropriate methodologies for the County of San Diego. The methodologies will address planning for design in undeveloped watersheds under normal conditions, emergency response immediately following a fire, and planning for design in undeveloped areas that experienced wildfire in the past 2-10 years.

1.2 Current Treatment in 2003 San Diego County Hydrology Manual

The Hydrology Manual does not currently prescribe methods for post-fire hydrology adjustments or sediment bulking, though flows for some projects have previously been bulked for sediment using bulking factors of 1.5 to 2 (Gusman et al., 2011).

The Manual does prescribe near-term and long-term sediment yield calculation requirements for hydrology studies. After providing a list of existing methods used to quantify soil losses, the Manual introduces the Universal Soil Loss Equation (USLE) as the default method to be used in San Diego County, stating that other methods should only be used when engineers believe the alternative method will result in more accurate quantities and the method is approved by the reviewing agency.

The 2019/20 TAC recommended various revisions to the Hydrology Manual, including revisions to Section 5 (“Erosion and Sedimentation”). These included additional methods for computing soil loss and sediment yield, text updates/clarifications, and more up-to-date references and sources for additional information.

2 BACKGROUND

2.1 Sediment and Debris

Broadly, erosion is the loosening or dissolution and removal of earth and rock materials ("sediment") from the earth's surface. Materials may be eroded, or mobilized, by a variety of forces, including rain-splash, flowing water, wind, and human activity, then are typically transported and deposited in another location. While dry ravel can be the dominant erosion process in non-cohesive soils (Lamb et al., 2011), water is the primary agent responsible for eroding and transporting sediment downslope in the landscape, so the movement of sediment is an important consideration for flood control engineering projects (Vanoni, 2006).

In addition to sediment, vegetative debris sometimes comprises an appreciable portion of material transported from watershed hillslopes and into streams. The terms "sediment" and "debris" are each sometimes used to include both sediment and organic woody material, while sometimes they are used separately to distinguish between the material types. In this report, "sediment/debris" is generally used to include both categories.

Flood control infrastructure (dams, sediment/debris basins, channels, etc.) is designed to protect property and lives by safely conveying and storing flood flows, subject to economic and other constraints. Two concepts, sediment/debris yield and sediment/debris bulking, are particularly important for engineering design.

2.2 Sediment/Debris Yield

Sediment/debris yield is the quantity of eroded sediment and vegetative debris delivered to a basin outlet for a specified flood event or period. This quantity is typically smaller than the quantity of sediment/debris produced (eroded) in the watershed during the same event or period, due to the deposition and storage of sediment/debris within the watershed.

Sediment/debris yields for design storm events are sometimes computed at canyon mouths to inform the sizing of sediment/debris basins capable of capturing and temporarily storing excess sediment/debris, thus removing the need to accommodate the sediment/debris loading further downstream.

2.2.1 Sediment/Debris Delivery

The ratio of the sediment/debris yield to the sediment/debris production is known as the delivery ratio. It is typically expressed as a ratio where zero percent indicates no delivered sediment/debris (clear-water flow) and 100 percent indicates that all eroded sediment/debris is delivered to the outlet. Delivery ratios generally increase with watershed slope and decrease with watershed area; greater portions of produced sediment/debris are delivered to basin outlets for small, steep watersheds.

2.2.2 Watershed Factors Affecting Delivery

The rates and volumes of sediment/debris mobilized within a watershed and delivered to the basin outlet vary widely between watersheds and depend on a range of factors including topography, geology, soils, vegetative cover, and hydrology (Wohlgemuth & Lilley, 2018). Relationships between these variables are complex. For example, in very dry regions, sediment yield increases with decreasing aridity as more water is available to erode and transport sediment, but this trend reverses in wetter regions, where increased rainfall produces increased erosion-limiting vegetative cover and a decrease in sediment yield (Vanoni, 2006).

2.3 Sediment/Debris Bulking

Flood control facilities are typically sized to convey or store flow from a hydrological event with a defined return interval. Because sediment/debris displaces water and contributes to an increase in the volumetric flow rate and flood depth, design flows are sometimes increased beyond the clear-water flow rate to account for the role of the transported sediment/debris; this process is called sediment/debris bulking.

2.3.1 Typical Streamflows

The hydraulic characterization of clear-water streamflows benefits from the stable, predictable properties of liquid water. Most streams transport at least some sediment/debris, with variable rates depending on the upstream supply and the stream's available energy to transport the sediment/debris. During periods of normal streamflows with minimal vegetative debris, sediment concentrations in most rivers with large watersheds are less than 5 percent sediment by volume, while concentrations of 10-15 percent are common in small streams and alluvial fans[1] (O'Brien, 2006). For these periods of normal streamflow, the clear-water (no sediment/debris) discharge may reasonably be used as the design flow for flood control facilities.

2.3.2 Response to Watershed Disturbances and Large Storms

Along with streamflow, a stream's sediment supply frequently varies, particularly in response to watershed disturbances like wildfire, which increase the erodibility of soils, and large storm events, which provide more energy to mobilize and transport sediment from hillslopes and storage areas within the watershed. The complex interplay between increased flows and increased sediment supply often results in dynamic sediment concentrations characterized by pulses of high sediment loading, particularly on the rising limb of erosive storm flood hydrographs.[2]

During large storm events and particularly following wildfires, woody debris (logs and branches) is often flushed into streams, adding its volume to the overall flow. As the concentration of sediment/debris increases within a streamflow, the total flow volume increases and the hydraulic behavior of the flow changes due to increased density, viscosity, and shear strength relative to the clear-water flow.

2.3.3 Sediment/Debris Concentration

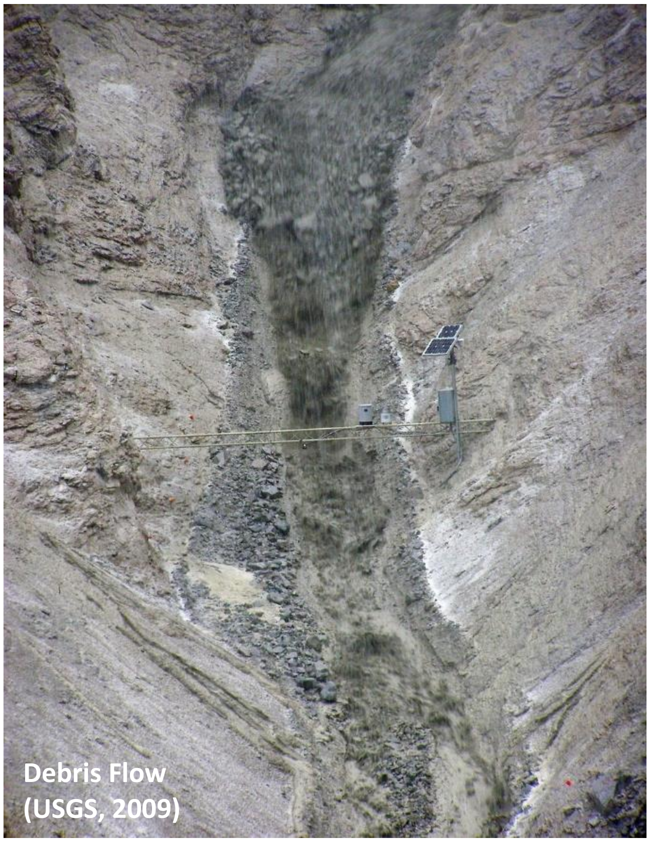
Streamflows are frequently categorized based on the concentration of entrained sediment and/or woody debris, the mechanism for suspending particles in the flow, and the associated

---

[1] Alluvial fans are sloped, fan-shaped landforms formed by the deposition of upland sediment, particularly at the base of semi-arid mountain ranges. While not a primary focus of this study, they are discussed in more detail in Chapter 4.

[2] Sediment loading generally decreases on the falling limb, due to the decreased supply following earlier removal of the most erodible soils and the deposition of entrained sediment due to the flow's reduced sediment transport capacity.

flow behavior. Above the concentration range for normal streamflow, hyperconcentrated flows begin to exhibit non-Newtonian (i.e., nonzero shear strength) properties, though sediment is still supported by turbulent flow stresses. At very high concentrations, cohesive yield stress and viscous shear stress dominate; these are called debris flows or mud flows, depending on the predominant size of the sediment particles. Finally, at extreme concentrations, sediment-water mixtures are generally considered landslides, with slow creep prior to block sliding failure (Gusman et al., 2011; Mussetter, 2008).


Debris Flow (USGS, 2009)

Precise definitions for each type of flow vary by author, and public agencies use different methods and definitions for transported material. Most researchers consider 20-percent sediment/debris concentration by volume as the upper limit for normal streamflow, but published threshold concentrations between hyperconcentrated flow and debris flow vary more widely—typically, the lower bound of sediment/debris concentrations at which debris flows occur is approximately 40 percent by volume (Gusman et al., 2011). The variation among researchers may be due in part to the dependence of flow properties on the type of transported material. Flows may exhibit non-Newtonian characteristics at much lower concentrations when the transported material is fine (Bradley, 1986).

The sediment/debris transported in normal streamflows and in hyperconcentrated flows is often mainly supplied from watershed hillslopes. While hillslopes generally contribute some sediment and debris to post-fire mud and debris flows, most mud and debris flow material is eroded from channels (Santi et al., 2006). Debris flows are particularly destructive.

2.3.4 Bulking Factor Calculations

When designing structures downstream of highly erodible areas, and particularly those areas subject to wildfires, engineers use different approaches to account for the additional flow volume and changes in flow behavior associated with high sediment/debris concentrations. Frequently, the clear-water discharge is computed based on a hydrological analysis, then the peak clear-water flow rate is multiplied by a factor greater than 1 to compute a design flow that includes the volumetric contribution of the entrained sediment/debris. This is known as a bulking factor, and it is equal to the ratio of the bulked discharge to the clear-water discharge (O’Brien & Fullerton, 1989; Elliott et al., 2005).

The bulking factor may also be computed based on the concentration of the total sediment/debris load in the flow by volume, using Equation 2.1, or by weight, using Equation 2.2, if those data are available.

$$Bulking\ Factor = \frac{1}{1-\frac{C_v}{100}} \qquad (2.1)$$

where C_v is the total sediment/debris concentration in percent volume (total sediment/debris volume divided by total flow volume).

$$Bulking\ Factor = \frac{1}{1-\frac{C_S\,/\,10^6}{S_g - (C_S\,/\,10^6)(S_g-1)}} \qquad (2.2)$$

where C_s is the total sediment/debris concentration by weight, in parts per million (ppm), and S_g is the specific gravity of the sediment (Mussetter, 2008).

2.3.5 Bulking Factor Application

In most cases, sediment/debris bulking factors are not applied to channels experiencing normal streamflow conditions,[3] and only hyperconcentrated flows and mud/debris flows are bulked (Gusman et al., 2011).

Standard bulking factors for a region may be prescribed based on historical observations for that region or assumptions based on literature, or a bulking factor may be computed for a particular watershed by distributing the sediment/debris yield for a design flood event over the design flood hydrograph and identifying the total (bulked) peak volume.

The application of bulking factors to design flows assumes channel systems are capable of transporting supplied sediment/debris, and sediment transport models or sediment transport capacity analysis may be used to evaluate this assumption. For example, consider the case of a channel and culvert designed to convey a 100-year design flow using a bulking factor of 1.4. Depending on the hydraulic design of the culvert, substantial sediment might be deposited upstream of the culvert during smaller events. This sediment might reduce the channel's capacity to convey the design flow and/or supply additional sediment to the culvert during a large event if the sediment is scoured, effectively increasing the sediment yield for the design event and the total flow volume at the culvert.

2.4 Effects of Wildfire on Clear-water Hydrology and Sediment

Wildfires can dramatically change the hydrological and sedimentological response of a watershed to even modest rainstorms (Silver Jackets, 2020), though the degree of these changes is sensitive to the size of the watershed.

Hydrologically, the loss of a vegetative canopy, leaf litter, and duff reduces interception, storage, and evaporative losses, while burned soils often become hydrophobic, limiting infiltration (DeBano 1981; Cannon et al., 2003; USDA, 2016). This produces increased runoff volumes (USDA, 2016), which arrive at basin outlets more quickly (reduced time of

---

[3] For a sediment/debris concentration of 20 percent by volume (the typical upper limit for normal streamflow), this corresponds to a bulking factor of 1.25. While this concentration is atypical in normal streamflow, it is *not* negligible for hydraulic design.

concentration) due to the removal of vegetative obstructions, resulting in larger peak flows. As a result, a 10-year rainfall event on a burned landscape might result in a 100- or 200-year peak flood (Conedera et al., 2003). Post-fire runoff increases proportionally more for smaller watersheds than for larger ones (Stoof et al., 2012).

Fire also combusts soil-binding organic matter, and this, coupled with the larger, faster overland flows, frequently results in accelerated stripping of sediment from hillslopes. Wildfire also dramatically increases the supply of woody debris to streams (USDA, 2016). Total debris production and yield may increase more than thirtyfold during the first year following a fire, before decreasing substantially in the second year and returning to normal in about ten years (California DWR, 1977; Rowe, Countryman, & Storey, 1949, 1954). Debris yields from extremely small watersheds may be even larger; Wells (1981) documented an event during which debris yield increased by over 100 times the normal rate from a recently burned, 0.02-acre watershed. Debris flows may take one to three years to return to pre-fire rates, while higher sediment transport rates may persist for a longer period (Santi & Morandi, 2012; Gartner et al. 2014; USDA, 2016).

2.5 Sediment/Debris Yield in Southern California

2.5.1 Storm Event Yield

In coastal Southern California, most sediment/debris yield from watersheds results from a small number of short-duration storms, particularly during wetter years (significant sediment yield occurs principally for saturated watersheds) and for smaller watersheds. Historically, the largest recorded unit sediment/debris yields in the region were delivered from recently burned watersheds that yielded little sediment/debris for an extended period, then experienced a large flushing event (or events) that remobilized extremely large quantities of previously eroded material from temporary storage in the watershed, scoured channels by removing bed material in debris flows and recession flows, and eroded the banks (Gatwood et al., 2000; Scott & Williams, 1978). Because of the importance of individual storms, sediment engineering design in Southern California typically focuses on specific event yields rather than average annual yields.

2.5.2 Transverse Ranges

Sediment/debris erosion and transport processes are extremely complex and can vary dramatically at the regional and even watershed scales (Inman & Jenkins, 1999; Warrick & Mertes, 2009). This complicates efforts to develop simple relationships that are generally applicable to a range of watersheds without being overly conservative.

Sediment/debris yields and bulking factors used for flood control infrastructure design by public agencies in Southern California are typically based on empirical regressions developed using data collected in the Transverse Ranges of Los Angeles, Ventura, San Bernardino, and Santa Barbara Counties (Gatwood et al., 2000; Gartner et al., 2014).

The Transverse Ranges include several east-west-oriented mountain blocks stretching over 300 miles from west of Point Conception, in Santa Barbara County, eastward into the Mojave and Colorado Deserts (see Figure 2-1). Most of the ranges are fault blocks, uplifted by tectonic movements late in the Cenozoic Era, and exhibit thrust faulting, strike-slip faulting, and bedrock folding (Dibblee, 1982; Inman & Jenkins, 1999). The formations are predominantly unconsolidated and easily eroded Cenozoic sediments of Pliocene through Eocene age (Inman & Jenkins, 1999). With their steep slopes, non-cohesive soils, bedrock weakened by high rates of tectonic uplift (Warrick & Mertes, 2009), and the semi-arid climate, watersheds in the Transverse Ranges are highly erosive by global standards (Wohlgemuth & Lilley, 2018; Gatwood et al., 2000) and feature among the highest erosion rates in the continental United States under normal conditions (Neely et al., 2019; Scott & Williams, 1978).

Figure 2-1. Map of Transverse Ranges and other Geomorphic Provinces in Southern California (Excerpt from California Geological Survey, 2018, used with permission)

Wildfires, which are increasingly common (Lamb et al., 2011) and intense (Silver Jackets, 2020) in the region, present an additional ecological disturbance that dramatically accelerates both surface runoff and erosional processes.

These factors, taken together with the increased development on floodplains and alluvial fans—areas with high erosion and deposition rates (Gatwood et al., 2000)—produce a risk of extreme sedimentation events in the Transverse Ranges that is among the highest globally (Kean & Staley, 2021a).

2.5.3 Regional Sediment/Debris Yield and Bulking Factors

Regional efforts to characterize sediment/debris yields and bulking factors have focused on the Transverse Ranges for two reasons:

First, characterizing and predicting sediment-related hazards is of particular importance to affected communities; modeled forecasts for major debris flows suggest that locations that have experienced major events in the past, primarily including steep basins in the San Bernardino, San Gabriel, and Santa Ynez Mountains, are also the most susceptible to future events (Kean & Staley, 2021a).

Second, the flood-control infrastructure developed to mitigate sediment hazards in the Transverse Ranges—principally, sediment/debris basins—has permitted the collection of historical data required for the development of predictive empirical models. This is a *critical point*: Data on post-fire debris-flow volumes are very rare because (1) sediment/debris basins themselves are rare outside of the Transverse Ranges, (2) material is often removed from basins before volumes are measured, and (3) volume measurements must be accompanied by paired rainfall rate data to be useful (Jason Kean, personal communication, May 10, 2022).

Many methods have been developed for estimating sediment/debris yields and bulking flood flows in the Transverse Ranges, including following wildfires, and these methods are often applied in nearby counties for lack of a better alternative, particularly during post-fire emergency assessments.

2.5.4 Application to Less-Erosive Areas

While the use of methods developed for the Transverse Ranges may be reasonable in many parts of Southern California, watershed characteristics differ substantially in some less-erosive areas in the region, including portions of San Diego, Riverside, and Orange Counties (Gatwood et al., 2000). For example, in addition to differences in the geology and surficial soils, San Diego County's Peninsular Range watersheds have smaller relief and hillslope angles compared to the Transverse Ranges (Jason Kean, personal communication, May 6, 2022). Unfortunately, the very limited observational data available for these less-erosive areas limits researchers' ability to calibrate locally appropriate regression equations. Differences between the Transverse and Peninsular Ranges are explored further in Section 4.2.

Based on this context, this study seeks to identify a) whether and where sediment/debris-related hazards should be planned for in San Diego County, b) whether and how existing methods developed for the Transverse Ranges can be adapted and applied to produce conservative, reasonable estimates of sediment/debris yields, and c) appropriate bulking factors for flood control infrastructure design.

3 SEDIMENT/DEBRIS YIELD AND BULKING METHODS USED IN SOUTHERN CALIFORNIA

In 2011, WEST Consultants, Inc. prepared a comprehensive report (Gusman et al., 2011) for the Ventura County Watershed Protection District detailing flow-bulking factor research and analysis relevant to Ventura County and providing policy recommendations. As part of the study, the authors reviewed sediment bulking methods used by other public agencies in Southern California and assessed their potential appropriateness for Ventura County.

As part of this study for San Diego County, we reviewed the current methods used by the same agencies described in the Ventura County report, to assess whether any had changed in the past decade. The results of the review underscore the reality that sediment bulking (particularly post-fire) is a relevant topic for municipalities and that San Diego County is not alone in seeking improved methods for quantifying the impacts of sediment on design flows. The following sections describe the approaches and highlight recent or planned changes.

3.1 Los Angeles County Flood Control District

The Los Angeles County Hydrology (Los Angeles County, 2006a) and Sedimentation (Los Angeles County, 2006b) Manuals have not been updated since the 2011 WEST Consultants report.

The Los Angeles County Sedimentation Manual prescribes methods for identifying both the event-based design sediment yield and bulking factor for a watershed. These methods are specifically developed for use in Los Angeles County and are based on locally collected, historical sediment data. The Sedimentation Manual divides the County into three basins. Within each basin, Debris Potential Area (DPA) zones are delineated based on areas with similar conditions and expected sediment yield volume productions. Both sediment yields and bulking factors are identified based on these DPAs; the former are used to size sediment retention basins and the latter are used to design channels in sediment-producing areas without sediment retention basins.

3.1.1 Sediment Yield

A Design Debris Event (DDE) is defined as the quantity of sediment yielded (“produced,” in the manual) by a saturated watershed recovered from a burn (4+ years later) after a 50-yr, 24-hr rainfall event—this is elsewhere referred to as the “Capital Flood.” Debris Production Rate (DPR, measured in cubic yards per square mile (per storm), yd^3/mi^2) curves are established for each DPA as a function of drainage area, where smaller areas generally produce sediment at higher rates. The DPR curves are found in Appendix B of the Los Angeles County Sedimentation Manual (Los Angeles County, 2006b); an example is shown in Appendix B of this report. The DPR obtained from the appropriate curve is multiplied by the drainage area to compute the design sediment yield (“Debris Production,” DP) in cubic yards.

The manual notes that for watersheds with slides or unstable slopes, a registered geologist must assess the additional sediment retention capacity potentially required on a case-by-case basis.

3.1.2 Sediment Bulking Factor

Appendix B of the Los Angeles County Sedimentation Manual (Los Angeles County, 2006b) also provides peak bulking factor curves for each DPA, based again on watershed area. The identified bulking factor is multiplied by the peak clear-water flow (which may have previously been increased to reflect post-fire conditions) to compute the bulked flow rate. An example of these curves is shown in Appendix B of this report.

Bulking factors range from 1.02 to 2; however, it not known if and how the current curves, which were most likely developed in the 1960s (Martin Araiza, personal communication, May 17, 2022), reflect the time since the last watershed burn. The manual states that the peak bulking factor curves indicate the proportion of the bulked flow rate to either the peak burned flow rate or to the clear-water flow rate if the watershed has no potential to burn; in other words, the increase in total flow volume (including sediment loading) is assumed to be proportional to any post-fire increase in clear-water flows. No evidence is given to support this assumption. Feasibly, updated curves incorporating an additional 50+ years of collected data and disaggregated based on the time since the last burn might yield different results, but Mr. Araiza noted there are no current plans to update the bulking curves.

In addition to the bulking factor curves, the Los Angeles County Sedimentation Manual suggests that an appropriate bulking factor for watersheds with different characteristics can be found using a procedure "similar to the procedures for determining sediment production explained in Section 3.3," though it is not clear how the sediment produced during the DDE would be distributed throughout the design hydrograph to find the peak bulking factor. Likely, this would be done using Equation 3.1, below, (Equation 3.4.9 in the Los Angeles County Sedimentation Manual), which according to the manual is typically used for sediment transport studies only. However, not enough information is given in the manual to solve the equation—either the bulking constant, *a*, or the bulking exponent, *n*, must be assumed at the outset, though no guidance about how to select an appropriate value is provided.

$$Q_S = a(Q_W)^n \tag{3.1}$$

where:

Q_S is the sediment discharge (cfs),

Q_W is the clear-water discharge (cfs), and

a and n are a bulking constant and exponent, fixed throughout the hydrograph.

According to Mr. Araiza, in practice, only the curves found in Appendix B are currently used by Los Angeles County Public Works for bulking flows. However, Mr. Azaria noted that if Equation 3.4.9 (Equation 3.1 in this report) were to be used, he would recommend starting with a bulking exponent, *n*, of 1.2 to 4, then solving for the bulking constant, *a*, such that the total volume under the sediment hydrograph equals the design sediment production volume. Then, the ascending and descending limbs of the resulting sediment hydrograph could be reviewed to assess whether the calculated sediment flows seem reasonable based on engineering judgment, and if not, the exercise could be repeated with a different bulking exponent, *n*.

3.2 U.S. Army Corps of Engineers (USACE) Los Angeles District

The USACE Los Angeles District Method for Prediction of Debris Yield ("Los Angeles District Method," Gatwood et al., 2000) was developed in 1992 based on statistical analysis of observed data from watersheds of various sizes (0.1 to 200 mi^2) in coastal (i.e., west of the coastal/desert drainage divide) Southern California, as shown in Figure 3-1. The method is intended for saturated watersheds predominately comprised of steep, mountainous, undeveloped terrain, and should not be used for watersheds with a high percentage of alluvial fan or valley fill areas. The method builds on the earlier work of Tatum (1963) by expanding the data used to develop the statistical relationships, and the authors envisioned further, future updates following the accumulation of new data. The Gatwood et al. report—but not the method or resulting equations—was updated in 2000 and has not been updated since.

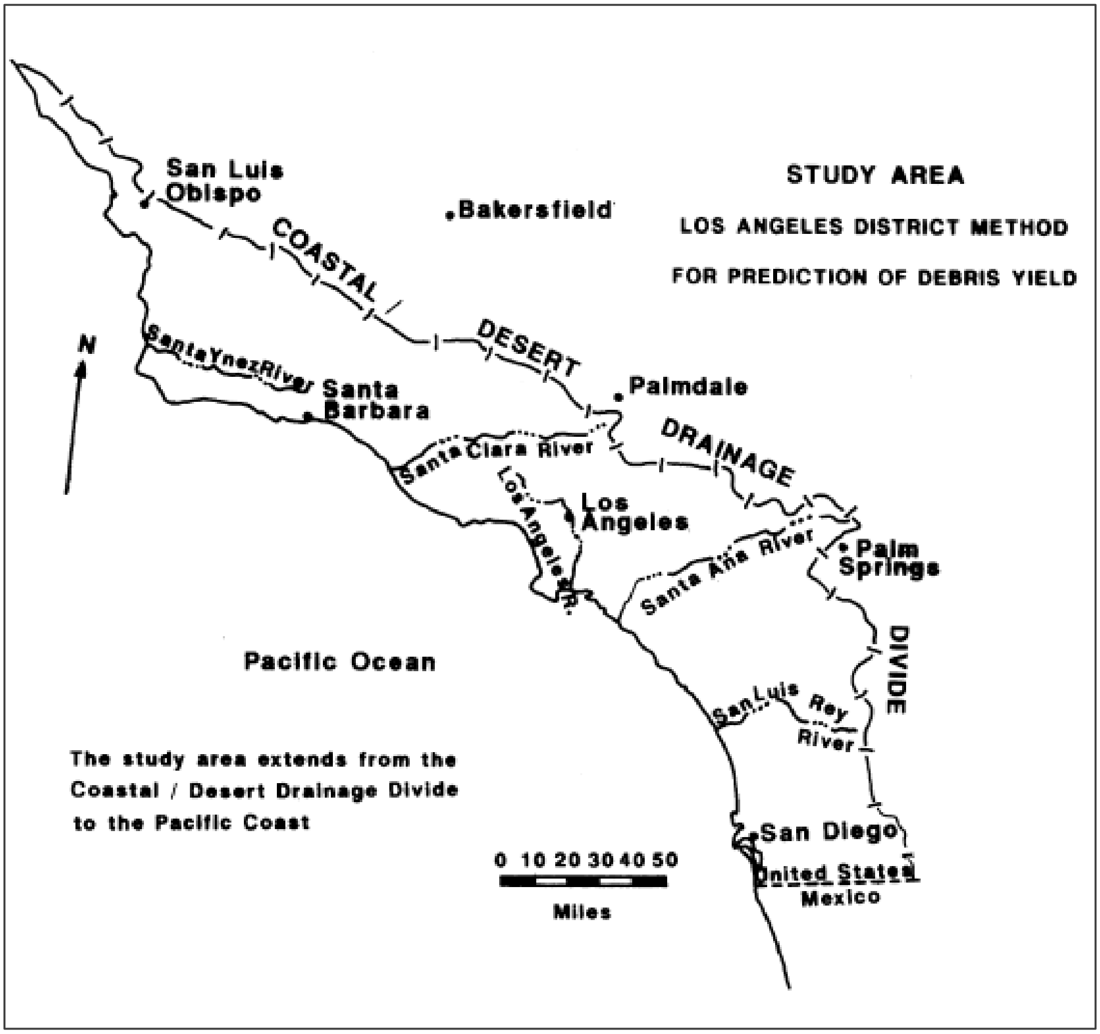


Figure 3-1. Principal Area of USACE Los Angeles Debris Method Application (Gatwood et al. 2000)

The Los Angeles District Method enables users to estimate unit debris yield values for "*n*-year" flood events based on the coincident frequency of wildfire and flood magnitude. Notably, the equations were developed based on measured debris volumes (debris yield) deposited in sediment basins and dams at the mouths of canyons,[4] and so rather than producing a bulking factor to be used in the design of downstream hydraulic structures, the equations are intended for use in sizing structures that will capture and store sediment delivered from singular storm events and be emptied between storms (thus removing or reducing the need to bulk downstream design flows). The method is used to estimate debris yields for flood events greater than those with a five-year recurrence.

To use the method, one of five multiple regression equations is selected based on the size of the watershed area, as shown in Table 3-1. The most important distinction is between that of the equation for the smallest watersheds (0.1 to 3 mi^2, corresponding to Equation 1) and larger watersheds (Equations 2 through 5). Because regional storms tend to have variable intensity over large areas, short-term precipitation (specifically, the maximum 1-hour precipitation) is a good predictor of debris yield for small watersheds where runoff data are not typically available, but runoff is a better indicator variable (and more readily available) for larger watersheds. Note that the nondimensional Fire Factor (FF) variable, which reflects both the number of years since the last watershed burn and the size of the burned area, is taken from a set of curves corresponding to the watershed area range. An example curve for watersheds 0.1 to 3.0 mi^2 is provided in Appendix C.

Equation 2 may be used for watersheds smaller than 3.0 mi^2 when peak runoff data are available, but the FF must be determined independently.

Table 3-1. Regression Equations for USACE Los Angeles Debris Method

No.	Equation	Watershed Size (mi^2)
1	$\text{Log}(D_y)=0.65(\text{Log}(P))+0.62(\text{Log}(RR))+0.18(\text{Log}(A))+0.12(FF)$	0.1 to 3.0
2	$\text{Log}(D_y)=0.85(\text{Log}(Q))+0.53(\text{Log}(RR))+0.04(\text{Log}(A))+0.22(FF)$	3.0 to 10
3	$\text{Log}(Dy)=0.88(\text{Log}(Q))+0.48(\text{Log}(RR))+0.06(\text{Log}(A))+0.2(FF)$	10 to 25
4	$\text{Log}(Dy)=0.94(\text{Log}(Q))+0.32(\text{Log}(RR))+0.14(\text{Log}(A))+0.17(FF)$	25 to 50
5	$\text{Log}(Dy)=1.02(\text{Log}(Q))+0.23(\text{Log}(RR))+0.16(\text{Log}(A))+0.13(FF)$	50 to 200

The variables include the following:

D_y = Unit Debris Yield (yd^3 / mi^2)

P = Maximum 1-Hour Precipitation (inches, to two places after the decimal, times 100)

Q = Unit Peak Runoff (ft^3/s / mi^2)

RR = Relief Ratio (ft/mi)

---

[4] When estimating sediment/debris yield at a location downstream of a canyon mouth, the authors recommend evaluating the transport capacity of the upstream channel during the design flood. If the stream is incapable of transporting the estimated debris quantity to the basin, the authors recommend considering use of the transport capacity as the adopted basin inflow debris estimate. While not stated, it should be noted that most sediment transport equations compute only bed sediment (bedload) discharge under uniform, steady flow, so care must be taken when using this approach to include any suspended load that would be trapped by the basin in the adjusted inflow debris estimate.

A = Drainage Area (acres)

FF = Nondimensional Fire Factor

Gatwood et al. note that because the equations were developed based on readily available data from the erosion-prone San Gabriel Mountains, direct use of the equations in areas with less-volatile erosional activity—such as the Peninsular Ranges of San Diego County—will result in overestimation of debris yield. To account for other important variables that differ in other parts of the region, such as surficial geology, soils, hillslope, channel geomorphology, etc., the authors describe the use of an appropriate Adjustment-Transposition (A-T) Factor, which is multiplied by the unit debris yield. For the San Gabriel Mountains, an A-T Factor of 1 is generally assumed, and in other coastal Southern California areas less prone to erosion, a factor of less than 1 should be used. Appendix B of the Los Angeles District Debris Method report discusses calculation of the A-T Factor and presents four different techniques, with each successive technique requiring less information and providing less certainty. The authors emphasize the importance of thorough investigation of all available local information and onsite evaluation of watershed characteristics to supplement application of the recommended regression equations and note that the method does not address the hazard associated with major landslides or mudflows.

The authors also note that in addition to potentially substantial differences represented in the A-T factor, the effects of wildfire in desert-draining watersheds east of the drainage divide will not be the same as those for coast-draining watersheds, and so great care must also be made to apply an appropriate FF variable in these areas. In desert watersheds where vegetal cover is minimal and debris yield is not substantially affected by wildfire, the Fire Factor is often fixed at an unburned value of 3.0.

3.3 Ventura County

Following preparation of the 2011 report by WEST Consultants, Ventura County published an updated version of its Hydrology Manual in 2017. The manual described two different options for computing bulking factors, both of which require initial computation of the sediment yield.

The first method is consistent with the previous version of the Hydrology Manual. Users first compute the expected sediment yield from undeveloped portions of a watershed using the Scott and Williams (1978) equation (developed for the western Transverse Ranges in Ventura County based on data collected for similar watersheds in Los Angeles County) or a similar method, then use a historic curve to find the bulking factor based on the computed sediment production in cubic yards per square mile. The historic curve for bulking factors (which range from 1.42 to 1.88) accounts for both the volume of sediment and floating debris and may include the increase in post-fire clear-water runoff, though the precise history of the curve is unknown (Gusman et al., 2011). The curve is currently used for the design of jurisdictional channels downstream of small watersheds that are known to be high sediment producers or subject to frequent fires, as well as for emergency projects and the design of critical development (Ventura County, 2017; Yunsheng Su, personal communication, April 25, 2022).

The second method was developed based on recommendations from Gusman et al. (2011) and follows concepts developed by the Los Angeles Department of Public Works. First, the volumetric sediment yield for a design clear-water hydrological event (the latter generated using the VCRat model) is computed using either a District-developed program, ScotSed, or a spreadsheet using the Scott and Williams (1978) regression equation. Next, Equation 3.1 (described previously) is used to distribute the total sediment volume throughout the flow hydrograph using a spreadsheet tool; the *n* bulking exponent value is assumed to be 3. The use of the second approach in several District studies has resulted in bulking factors of approximately 1.2.

Bulking factors are not applied for all infrastructure design, and the need for bulking is reviewed on a case-by-case basis. However, according to Mr. Su, almost all cases where bulking factors are applied in Ventura County are on alluvial fans or in areas with alluvial fan characteristics.

The 2017 Ventura County Hydrology Manual notes that recommendations and procedures for changing runoff parameters due to fires were still under development as of 2017, and that until the District's policy is finalized, fire effects will be modeled on a case-by-case basis after consultation with the District's Hydrology Section. According to Mr. Su, this guidance remains current.

Note: While not currently used in Ventura County, Gusman et al. (2011) identified conservative bulking factors for two burn conditions (100% burned basin 4.5 years after a fire (FF = 20) and 100% burned basin 6 months after a fire (FF = 88) and two watershed size classes (≤3 mi^2 and >3 mi^2), based on historical sediment and flow data collected in Ventura County. These are presented in Table 3-2 and provide a useful reference.

Table 3-2. Conservative Bulking Factors – Ventura County (Gusman et al., 2011)

Project	Bulking Factor	
	Drainage Area ≤ 3 mi^2	Drainage Area > 3 mi^2
Design (FF = 20)	1.6	1.2
Emergency (FF = 88)	1.75	1.25

3.4 San Bernardino County

According to the 2011 WEST report, at that time a bulking factor of 2 (50% sediment, 50% water) was applied to all flows where bulking was required.

Currently, a bulking factor of 2 is still applied for recently burned watersheds (Michael Fam, personal communication, April 12, 2022), and the Los Angeles District Method is used to compute a predicted post-fire debris volume for sizing sediment basins. The method is implemented using a standard spreadsheet calculator and the Los Angeles District Method FF curves with an A-T factor of 1.

Mr. Fam said that flows are also bulked pre-fire for all other undeveloped land with no debris basin upstream of the flood control facility, but noted there are currently no standard guidelines and bulking factors are determined on a case-by-case basis. Typical sediment bulking factors have ranged from 1.5 to 2 for pre-fire projects. Mr. Fam expressed interest in the current San Diego County study and suggested that San Bernardino County may pursue a similar formalization of sediment yield and bulking guidelines.

While this method is not published, the San Bernardino County Department of Public Works Water Resources Division also modifies basin hydrological analyses post-fire by adjusting modeled runoff parameters for soil, based on knowledge of watersheds and engineering judgment (Ibram Gayed, personal communication, April 12, 2022).

3.5 Riverside County

The current Riverside County Hydrology Manual (Riverside County, 1978) does not prescribe a particular method for sediment bulking, due to a lack of historical debris production data, but instead describes two methods—the Los Angeles County Flood Control District and USACE Los Angeles District methods—that were developed based on data collected in Los Angeles County and might be relevant. The Manual emphasizes that the applicability of the Los Angeles County data and methods must be evaluated by competent engineers and geologists on a case-by-case basis.

In practice, the Riverside County Flood Control and Water Conservation District (RCFCWCD) has previously used the Tatum method (Tatum, 1963) and currently relies primarily on the Los Angeles District Method. The A-T factor for each watershed is determined using the fourth technique described in Gatwood et al. (2000), based on observed watershed characteristics and the judgment of a geologist. Post-fire, Riverside County relies on Federal and State-led emergency assessment analyses when they are available (see Section 3.7). Often, multiple methods are used, and the results are compared as a basis for engineering judgment (Kyle Gallup, personal communication, April 20, 2022).

Mr. Gallup said the RCFCWCD is currently preparing a Request for Proposals to develop a dedicated debris method for Riverside County. The District intends to require application of the method in unincorporated, debris-prone areas, with a focus on debris basin design or channel design if there is no upstream basin.

Following a fire, the RCFCWCD adjusts the watershed hydrology by changing the Runoff Index (RI value) to represent barren land, increasing the impervious percentage, and modifying the roughness coefficient (typically, reducing the n value to reflect a loss of vegetation and roughness), with a focus on the 2-, 5-, and 10-year events.

3.6 Orange County

Orange County Public Works does not currently prescribe a specific method for sediment bulking, though clear-water hydrology is typically prepared for a post-burn area, and then an appropriate bulking factor is applied on a case-by-case basis (Penny Lew, personal communication, April 14, 2022).

Orange County is currently working with a consultant to update its hydrology manual, and the scope of work includes a section on post-fire hydrology, though at the time of this study, work had not yet begun on this section of the manual.

3.7 BAER/WERT

Following a major wildfire in California, many public agencies coordinate to assess flood and sedimentation hazards and support efforts to mitigate those hazards and protect life-safety, property, and resources (collectively known as “critical values”). Each stakeholder operates under their own agency, guidelines, and funding, and precisely which agencies become involved at each stage depends on the characteristics of the fire. For example, the Federal Emergency Management Agency (FEMA) may be activated to respond to a fire if a Presidential Emergency Declaration is made, and FEMA may in turn enlist the USACE to aid in cleanup efforts.

In 2020, the Silver Jackets, a partnership program that brings together Federal, State, local, and Tribal agencies to find collaborative solutions to complex flood risk management issues, published “Flood After Fire,” the first version of a useful guide and toolkit for professionals planning for and responding to fires in California (Silver Jackets, 2020). The report simplifies the multi-level, multi-agency timeline of emergency fire response into three-time tiers, outlining the typical activities associated with each tier. Each tier is characterized by its timing, the agency responsibility/involvement, the data available to agencies, and the fidelity of the hydrology and hydraulics analytical methods used. Generally, analyses completed in Time Tier 1 are rapid and are designed to identify short-term, serious hazards and collect data to be used for future analyses. During Time Tiers 2 and 3, hydrologic and hydraulic models are refined using additional data, planning and mitigation strategies progressively focus on longer-term recovery of the burn area, and mitigation measures are implemented.

Appendix 6.1 of the Flood After Fire report provides a Resource Timeline Matrix describing common fire response needs, methods, sources used, and responsible stakeholders in a tabular format, categorized by time tier; this resource may be found at the following website address: https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll2/id/7452.

Two important stakeholders in California fire response are Federal Burned Area Emergency Response (BAER) teams, deployed by the US Forest Service (USFS) and the Department of the Interior (DOI), and State Watershed Emergency Response Teams (WERT), deployed by the State of California. These teams perform rapid (usually 1-to-2-week) responses during Time Tier 1, often beginning before fires are contained, and collect data and perform analyses to help inform short- and long-term mitigation and recovery efforts by various agencies and private sector firms. While each group focuses primarily on its own area of responsibility, BAER teams and WERT frequently coordinate in their use of real-time data and state-of-the-art methods on large fires and share many attributes, so for the purposes of this study their methods are presented together. A brief description of each group is provided below, followed by a summary of their post-fire hydrological and sediment-related assessments.

3.7.1 BAER

Federal BAER teams have responded to fires since the mid-1970s and are mobilized to provide a rapid assessment of post-fire threats to life and safety, property, and critical natural and cultural resources on National Forest System lands due to fire and to prescribe emergency stabilization treatments (Silver Jackets, 2020; USFS, n.d.). By USFS mandate, all fires larger than 500 acres, or smaller fires with suspected threats to BAER critical values, should receive some level of assessment. While the BAER program is only responsible for Federal lands, BAER teams often assess the entire fire area and communicate threats to non-Federal values to the appropriate jurisdiction or agency in an advisory capacity. However, the time and effort spent by BAER teams assessing non-Federal lands is usually very limited (Silver Jackets, 2020).

BAER teams include a variety of professionals, including hydrologists, soil scientists, engineers, biologists, vegetation specialists, archeologists, GIS specialists, and others; these may be employees of different agencies depending on whether the BAER team is deployed by the USFS or DOI. BAER team members conduct field surveys and use science-based models to rapidly evaluate and assess the burned area.

The BAER team presents its findings in an assessment report that describes pre- and post-fire watershed response information, identifies areas of concern for life and property, and recommends short-term emergency stabilization actions needed to address post-fire risks. The reports generally focus on severely burned areas, steep slopes, and parts of watersheds where excessive storm runoff may threaten important resources.

3.7.2 WERT

Post-fire assessments on non-Federal lands in California have been conducted by the California Department of Forestry and Fire Protection (CAL FIRE) and other State agencies using different approaches since 1956; since 2015, WERT have been utilized by the State to provide a similar function to BAER teams with a focus on state and private lands (“State Responsibility Areas,” or SRA). Like BAER teams, WERT analyze risks in watersheds immediately after wildfires and recommend actions, but WERT evaluations are narrower in scope and focus only on selected wildfires with substantial life and safety, infrastructure, and property risks (collectively, “values-at-risk”) from debris flows, flooding, and rockfall (Silver Jackets, 2020).

Like BAER teams, WERT also include a variety of professionals, but the teams are usually smaller with a focus on geology, hydrology, civil engineering, and GIS. Team members are typically employees of CAL FIRE and the California Geological Survey (CGS), and may also include members from the California Department of Water Resources (DWR) and/or the California Regional Water Quality Control Boards (RWQCBs). After making their assessments, WERT convey values-at-risk locations and recommended risk mitigation measures to local agencies for rapid implementation.

3.7.3 Flood and Debris Flow Risk Assessment

BAER teams and WERT begin their respective post-fire evaluations by obtaining a Burned Area Reflectance Classification (BARC) map produced by the USFS Remote Sensing Applications Center (RSAC) and the United States Geological Survey (USGS) EROS Data Center (EDC). Remotely sensed reflectance values before and after a fire are compared to produce a map of differenced Normalized Burn Ratio (dNBR), which is then processed to produce a BARC map with classified burn severity regions.

BAER teams and WERT use the BARC maps as a starting point, then refine the reflectance-based burn severity regions using belowground soil burn severity indicators observed during field surveys. The final product is a Soil Burn Severity (SBS) map, which identifies areas of soil burn severity by categories of very low/unburned, low, moderate, and high, and is used as a modeling input for other analyses predicting watershed response (Silver Jackets, 2020). Figure 3-2 shows an example of a BARC map for the 2018 Woolsey and Hill fires in Ventura and Los Angeles Counties, along with the final SBS map.

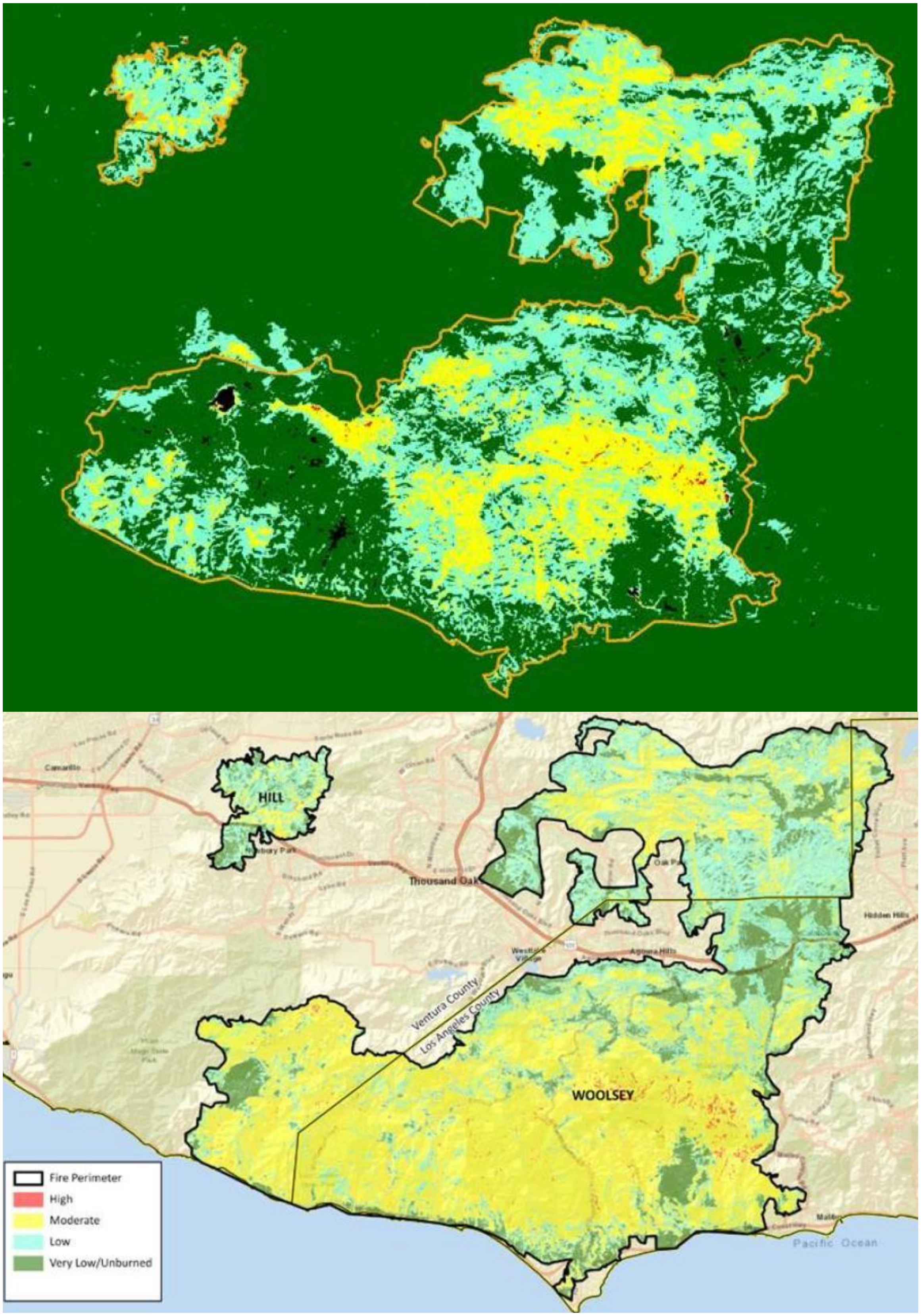


Figure 3-2. BARC map (top) and final SBS map (bottom) from the 2018 Woolsey Hill fires in Ventura and Los Angeles Counties, California (Silver Jackets, 2020)

After the final SBS map has been completed, BAER teams and WERT typically produce three types of post-fire hazard assessments: peak flow/flood response, geologic hazards (including debris flows and rockfall), and surface soil erosion. These products are in turn used to help determine the threat vector and level of risk to values-at-risk locations.

3.7.3.1 POST-FIRE HYDROLOGY

Post-fire flood response is evaluated at the watershed scale, most commonly by defining basin outlets, or "pour points," corresponding to values-at-risk sites within or near the fire area. Often, basin outlets are defined at or close to the fire perimeter. The percent of each watershed area burned at each SBS category is determined using GIS analysis. Pre-fire flood flows are determined for selected recurrence interval storm events—typically, the 2-year, 5-year, and 10-year events. The flows are often identified using the USGS StreamStats online tool (https://streamstats.usgs.gov/ss/), unless appropriate streamgage information is available within the watershed.

Post-fire flow peaks are then estimated using one of many different approaches that vary based on the region and team. Post-fire hydrologic science suffers from a lack of historical data, and so while BAER teams and WERT apply and compare the limited available objective methods whenever possible, ultimately, they rely on professional judgment and appropriate factors of safety depending on the downstream values or resources at risk (Don Lindsay, personal communication, May 31, 2022).

According to Don Lindsay of the California Geological Survey, teams often follow the following general pattern:

1. Perform a historic records search to determine the type and magnitude of past post-fire runoff events in the area under similar geoclimatic conditions that persist to the present. Where possible, runoff events are connected to a triggering rainfall event of known intensity and duration.
2. Conduct a rapid assessment of the channel morphology to determine the types of flow events that have occurred in the past and their relative age and magnitude. This information is sometimes also used to help identify an appropriate sediment bulking factor to apply to post-fire runoff hydrographs.
3. Identify a range of post-fire runoff models that can be applied to the watershed in question, based on the watershed characteristics, region, available data, etc., and apply those models.
4. Review the modeled results in light of information obtained during Steps 1 and 2.
5. Provide a final recommendation on the likely post-fire flow type and magnitude based on a mix of the available data, model results, and professional judgment.

Step 3 is of particular interest to researchers given the objectivity of the available approaches, and so is also the focus here. Models evaluated for a given watershed might include basic rules-of-thumb, empirical models, and complex, physics-based models.

The method proposed by Rowe, Countryman, and Storey (RCS) (1949 & 1954) is among the most commonly used empirical methods available for Southern California. The authors developed 256 look-up tables for Southern California watersheds, based on extensive observations of pre- and post-fire streamflows from 1869 through 1949, and these provide a useful reference for rapid, post-fire estimates. Unfortunately, while the method is well understood and simple to apply, it is very inaccurate for small watersheds (Silver Jackets, 2020; Wilder et al., 2020). Also, Wilder et al. note that a statistical flood-frequency approach to post-fire modeling—a model that uses return periods and probabilities of occurrence such as RCS—will decrease in reliability over time as the climate changes.

Recent research by Dr. Alicia Kinoshita's Disturbance Hydrology Lab at San Diego State University reviewed the RCS method and four methods commonly used by BAER teams and WERT for estimating post-fire peak flows (Kinoshita et al., 2013) and proposed a novel three-dimensional polynomial function to calculate post-fire peak streamflow in small to medium-sized watersheds (1 to 42 km^2) in Southern California during the first year after fire (Wilder et al., 2020). While the new Wilder (2020) method offers some benefits, it also has disadvantages, and currently there is no superior, simple method for estimating post-fire peak flows.

Sometimes, the choice of methods also depends on the availability of local resources. For example, if a given county has existing calibrated hydrologic and hydraulic models and available, qualified staff, BAER teams and WERT may work with the county staff to rapidly modify model input variables to reflect post-fire conditions, as another option (Drew Coe, personal communication, May 31, 2022).

Regardless of the method used to estimate the post-fire peak runoff, sediment bulking factors are often applied to develop a final peak flow as a conservative approach (Silver Jackets, 2020), though sediment bulking is already implicit in some methods (Wilder et al., 2020). Typically, increases in post-fire peak flows relative to pre-fire flows are reported as percentages rather than absolute increases in flow magnitude, to aid analysts in identifying potential flood hazards within or near a burn area (Silver Jackets, 2020).

3.7.3.2 POST-FIRE DEBRIS FLOWS

Following finalization of the SBS map for the burned area(s) by a BAER team and/or WERT, the map is sent to the USGS Landslide Hazards Program team in Golden, Colorado. That team rapidly estimates both the probability of debris flows and their potential volume yields following a design storm in the burned area.

The debris flow probability model uses a variety of inputs including basin shape, slope gradient, SBS, soil properties, and rainfall characteristics (Staley et al., 2016; Staley et al., 2017); debris flow likelihood increases for steep watersheds with fine soils having moderate and high SBS classifications and exposed to high-intensity, short-duration rainfall. Notably, the rapid-assessment model does not include factors like geology, because of the need for data that are nationally available (Jason Kean, personal communication, May 10, 2022). Other important factors and detailed data may be included in physically based models developed at a later stage.

Debris flow volumes are currently estimated using Gartner et al. (2014), an empirical model developed for and calibrated to watersheds in the highly erodible Transverse Ranges. Notably, the model does not include inputs for geology or surficial soils. The Gartner et al. (2014) model is used in every emergency hazard assessment conducted in the United States by the USGS Landslides Hazards Program, for lack of a better alternative (Jason Kean, personal communication, May 10, 2022)—as previously described, debris data are scarce and have mainly been collected in the Transverse Ranges. At the time of writing, the USGS was conducting research to improve the volume model using new pre- and post-event Light Detection and Ranging (LiDAR) datasets, but Mr. Kean (personal communication, May 10, 2022) noted this will be a long-term effort.

Despite its limitations, the Gartner et al. (2014) model was developed using data from debris flows that started primarily from distributed runoff and erosion, as opposed to discrete shallow landslides, so it does correctly scale volume estimates with drainage area and is useful in a relative ranking sense. Also, Mr. Kean (personal communication, May 10, 2022) noted the considerable uncertainty in volume estimates even for the Transverse Ranges, and explained that experts typically focus on the order of magnitude volume classes rather than exact volume predictions.

Debris flow probabilities and volume yields may either be presented separately or in a combined hazard map showing areas of low, moderate, and high hazard, where a high hazard classification indicates both a high probability of occurrence and a large volume of debris. Hazard maps may also either be presented on a drainage basin scale (with basins shaded to indicated classification), or by stream segment.

Figure 3-3 presents examples of maps showing the likelihood of debris flow (as a percentage), the potential volume of debris flow (in m^3), and the combined relative debris flow hazard for a portion of the 2020 Valley Fire burn perimeter in San Diego County, all made at the drainage basin scale and based on a design storm with a peak 15-minute rainfall intensity of 24 millimeters per hour (mm/h). Note the arrow on Figure 3-3(a) indicating a small, high-probability basin near Barrett Lake. Figure 3-4 shows a recent (May 2022) photo of this basin, giving a sense of scale and the amount of regrowth nearly two years post-fire.

Note that in Figure 3-3, the basins with the highest probability of debris flow occurrence are not the same as those with the largest potential debris volumes, in this case resulting in no high-hazard basins in the combined hazard map. Debris flow model results for this and other past wildfires may be viewed at: https://landslides.usgs.gov/hazards/postfire_debrisflow/.

After receiving the debris flow hazard maps from the USGS, BAER teams and WERT combine these with various GIS layers and field analysis to evaluate potential hazards to values-at-risk locations.

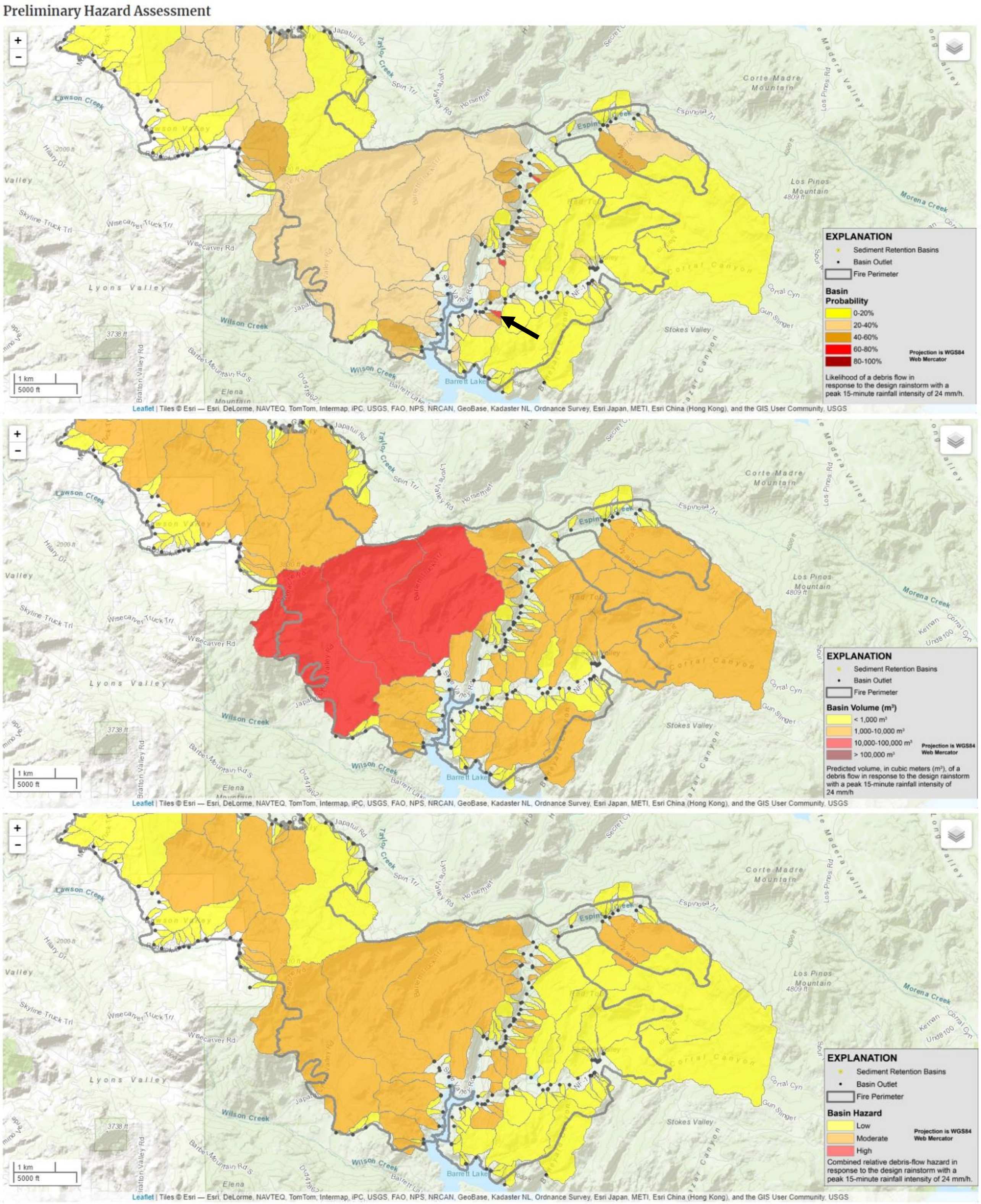


Figure 3-3. USGS debris flow model maps for the 2020 Valley Fire on a drainage basin basis, showing (from top) a) debris flow probability, b) debris flow volume, and c) combined debris flow hazards.

Figure 3-4. This May 2022 photo shows a small watershed near Barrett Lake (see arrow in Figure 3-3(a)) with a high probability of debris flow occurrence after the 2020 Valley Fire. Due to its small potential debris volume, the combined hazard is moderate (Photo: J. Viducich, River Focus).

3.7.3.3 SURFACE EROSION HAZARDS

Following a fire, BAER teams and WERT model both hillslope erosion rates (detachment and mobilization of sediment particles) and watershed sediment yield (the volume of sediment delivered to the fluvial system), typically using the same pour point locations associated with values-at-risk locations.

Most commonly, BAER teams and WERT use a batch version of the Erosion Risk Management Tool (ERMiT), a web-based Forest Service application that uses Water Erosion Prediction Project (WEPP) technology to estimate erosion, in probabilistic terms, on burned and recovering forest, range, and chaparral lands with and without the application of erosion mitigation treatments (Silver Jackets, 2020). Model inputs include location, vegetation type, soil type, topographic factors, and SBS class (Robichaud et al., 2011).

Other erosion models are occasionally used; these are often also based on WEPP and frequently allow users to evaluate both post-fire flow increases and hillslope erosion in the same model. Examples include the following (Silver Jackets, 2020):

- Automated Geospatial Watershed Assessment (AGWA)
- WEPP/GeoWEPP/QWEPP
- WEPP cloud, WePPCloud for Lake Tahoe and WEPP PEP
- Rapid Response Erosion Database (RRED-QWEPP)

3.8 Comparison of Methods

This survey of sediment yield, bulking, and post-fire hydrology methods used in Southern California reveals several key themes, including the complexity, diversity, and non-stationarity of regional sediment responses to storms and the limits of available sediment data useful for developing empirical methods, particularly for San Diego County. Table 3-3 summarizes the key output associated with each method, along with its advantages, disadvantages, and potential relevance to San Diego County.

Table 3-3. Comparison of Regional Methods and Relevance to San Diego County

Agency/Method	Method Output	Advantages	Disadvantages	Relevance to San Diego County
Los Angeles County Flood Control District	Sediment yield, sediment bulking factor	Simple to apply based on established curves, watershed size and location	Time since burn not clearly represented; may not be conservative immediately following fire. Difficult to apply outside of LA County.	Should data (e.g., paired rainfall and sediment basin cleanout volumes) become available in the future, it could be useful to develop similar curves specific to San Diego County. The LA County curves cannot be directly applied in San Diego County. *Applicability*: None
Los Angeles District Method	Sediment yield	Enables users to estimate unit debris yield values for "*n*-year" flood events based on the coincident frequency of wildfire and flood magnitude. Includes guidance to apply computed yield to less-erosive watersheds using an appropriate A-T Factor. Equations cover a wide range (0.1-200 mi^2; compared to 0-30 km^2 for Gartner et al. (2014)). Model is based on fire perimeter data rather than soil burn severity (SBS), so more data exist for smaller fires.	Does not provide a direct method for computing sediment bulking factor. Does not include additional data collected since 1992. Not intended for use on alluvial fans. Does not include most explanatory data for debris yield production.	While the Los Angeles District Method would benefit from an update incorporating newer sediment data, it performed comparatively well with the Gartner et al. (2014) model, it depends on data that are readily available, and it can be used for a wide range of watersheds and fire sizes. The A-T Factor allows for some prescribed adjustments of predicted yields based on watershed differences, including geology. The coincident frequency analysis can be performed in the U.S. Army Corps of Engineers' HEC-SSP (Statistical Software Package), generally following the guidance in the Los Angeles District Method report, allowing for debris basin design based on the 1% exceedance probability debris event. *Applicability*: Planning/design and emergency response
Ventura County	Sediment yield, sediment bulking factor	Relatively simple to compute hydrology, sediment yield, and sediment bulking factor using tools (VCRat, ScotSed, historic bulking curve, spreadsheet) developed and published by Ventura County.	The history of the more-conservative bulking factor curve used for design of jurisdictional channels downstream of small watersheds with high production and/or emergency projects is unknown and it may be less reliable. For the method used to distribute the yielded sediment volume throughout the design hydrograph, selection of a standard *n* bulking exponent value is not adequately supported.	Sediment yields computed using the Scott and Williams (1978) regression will not be appropriate for San Diego County because they were developed specifically for a portion of the Transverse Ranges with very high erosion rates. The method used to distribute sediment throughout the design hydrograph probably provides a reasonable starting point and could be used in San Diego to compute an appropriate bulking factor, or bulked peak flow, for a given watershed based on a design sediment yield. However, future study should be made to support the conservatism of the assumption that the sediment and water flow contributions always peak at the same time and that the *n* bulking exponent value should be fixed at a given value (e.g., 3). Sediment supply in flashy, ephemeral or seasonal streams often decreases over the course of a storm as readily erodible materials are progressively removed from the watershed, and higher sediment loading on the rising limb might feasibly result in a larger total bulked peak flow. However, given the magnitude of other uncertainties, this difference may be negligible. *Applicability*: Planning/design and emergency response
San Bernardino County	Post-fire sediment yield and bulking factor (pre-fire methods are not standard)	Los Angeles Debris Method is easily applied using spreadsheet tool. A standard bulking factor for burned areas is simple to apply.	Standard bulking factor of 2 for all post-burn areas is likely overly conservative. No defined pre-fire methods.	None; post-fire, Gartner et al. (2014) is likely a better choice for San Diego County watersheds. *Applicability*: None
Riverside County	No standard methods currently	N/A	N/A	N/A
Orange County	No standard methods currently	N/A	N/A	N/A

Table 3-3 (Continued). Comparison of Regional Methods and Relevance to San Diego County

Agency/Method	Method Output	Advantages	Disadvantages	Relevance to San Diego County
BAER/WERT	Post-fire peak flow, post-fire debris flow probability and volume, surface sediment erosion and yield	Methods represent the state-of-the-art approaches for post-fire analyses. Model used to compute debris flow yield, from Gartner et al. (2014), incorporates our best understanding of the explanatory variables for debris flow and sediment-laden flows. While it was developed using data for the Transverse Ranges, other research suggests the same input variables with slightly different coefficients are broadly applicable in the Intermountain West (Gartner et al., 2014).	These methods are intended to be used for post-fire emergency assessments to inform responses to mitigate immediate hazards for a particular watershed, rather than informing the design of infrastructure before fires to accommodate a generalized design event (e.g., a 100-year recurrence debris flow). Debris flow methods, and particularly volume predictions, are calibrated to watersheds in the highly erodible Transverse Ranges and may overestimate sediment volumes in San Diego County.	Analysis outputs will be developed by BAER teams and WERT for sufficiently large fires in their responsibility areas and provided to local agencies/jurisdictions. For other, smaller fires that do not receive BAER/WERT study, the County or other jurisdictions could feasibly contact the USFS or DOI for imagery and BARC support (available on a cost-reimbursable basis) and perform similar analyses to assess hazards. Notably, Kean and Staley (2021a) used the same empirical models for debris flow likelihood (Staley et al., 2017) and volume (Gartner et al., 2014) to develop pre-fire debris flow probability and volume maps for Southern California. These maps are useful for identifying areas with the greatest sediment hazards based on historical burn severity and climate patterns, though the regional analysis is somewhat coarse in resolution (1 km^2 cells) and the debris flow volume method relies on the interagency Monitoring Trends in Burn Severity (MTBS; https://www.mtbs.gov/) program, which only maps fires 1,000 or larger in the Western US. This might exclude some fires of interest. *Applicability*: Emergency response. Some methods can also be applied to planning/ design, though not used in this way by BAER/WERT.

4 SEDIMENT/DEBRIS HAZARDS IN SAN DIEGO COUNTY

4.1 Probability of Post-fire Debris Flows

Kean and Staley (2021a) mapped the probability of post-fire debris flows across Southern California, from Santa Barbara County to San Diego County. While the mapping approach is the same as the BAER team analysis described in Section 3.7, which is conducted immediately post-fire for a watershed, the Kean and Staley (2021a) analysis was performed as a pre-fire planning tool assuming median soil burn severity conditions for post-fire conditions.

A post-fire debris flow is caused by the occurrence of two primary events—first, a wildfire occurs, followed by a storm with sufficiently intense rainfall to cause a debris flow. According to Kean and Staley (2021a), the annual probability of a post-fire debris flow event can be computed as the intersection of the probability of a wildfire event and the probability of a storm event with rainfall intensity above the triggering threshold for debris flows, as illustrated in Figure 4-1.

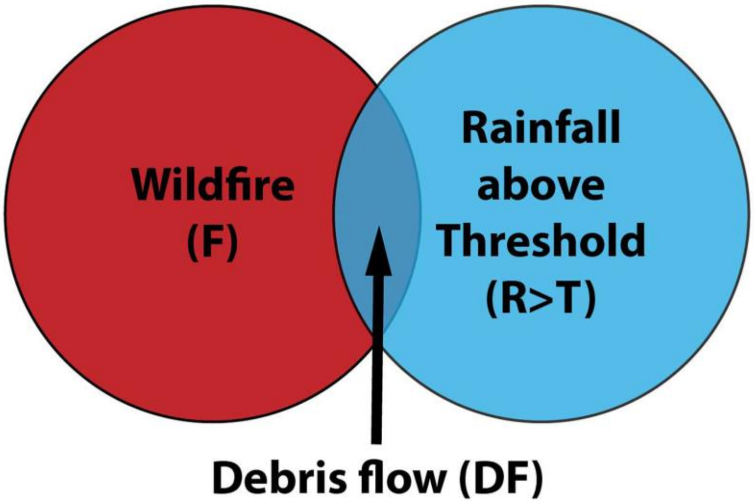


Figure 4-1. Debris Flow as the Intersection of Wildfire and Intense Rainfall (Kean & Staley, 2021a)

In Southern California, this threshold is linked to short-duration (less than 1 hour), high-intensity rainfall (Staley et al., 2017). The rainfall thresholds do not have a strong dependence on antecedent soil moisture conditions, which differs from those associated with shallow landslides (Kean et al., 2011).

4.1.1 Annual Probability of Major Debris Flows

Figure 4-2 provides a map of the expected probability of major debris flows in Southern California, ranging from green areas having a low probability of debris flow to red areas having the highest probability (Kean & Staley, 2021a). Major debris flow events are defined as those triggered by rainfall intensities that are at least 3 times the threshold (T) required to trigger any debris flow event, a condition corresponding to events that have damaged 40 or more structures.

As expected, the highest probability areas are found in the Transverse Ranges. This corresponds with the major historical debris flow events (circled in yellow and black on the map) used in the study, which all occurred in these same mountain ranges. In contrast, the study's dataset did not include any major debris flow events in San Diego County. Figure 4-3 shows the same major debris flow probability focused on San Diego County. Note that Kean and Staley (2021a) developed the debris flow probabilities based on gridded data with a 1 km^2 (0.386 mi^2) resolution.

4.1.2 Annual Probability of All Debris Flows

Figure 4-4 shows the probability of any size debris flow event occurring (major and minor) in Southern California. While the inventory of historical debris flows used for the study did not include any major debris flow events in San Diego County, some smaller debris flow events were documented. Figure 4-5 shows the same debris flow probability focused on San Diego County.

It should be noted that hyperconcentrated flows and small debris flows are more difficult to map systematically because they often require field work to document (Jason Kean, personal communication, May 6, 2022).

4.1.3 Annual Probability of Wildfires

The probability of fire occurrence used by Kean and Staley (2021a) is shown in Figure 4-6 for Southern California, and Figure 4-7 shows the same data, focused on San Diego County.

CAL FIRE (2022) has also developed fire hazard maps for San Diego County. Figure 4-8 presents fire hazard severity zones for State Responsibility Area lands in San Diego County. (See Section 3.7 regarding BAER teams/WERT and responsibility areas.)

4.1.4 Annual Probability of Intense Rainfall

Figure 4-9 shows the probability of intense, short-duration (less than 1 hour) rainfall in Southern California that can trigger a debris flow event. Figure 4-10 shows the same probability, with a map focused on San Diego County.

4.1.5 Sediment/Debris Volumes

Kean and Staley (2021a) also developed maps showing expected debris flow volumes throughout Southern California. However, as described in Section 3.7, flow volumes are currently estimated using Gartner et al. (2014), an empirical model developed for and calibrated to watersheds in the highly erodible Transverse Ranges. This model does not include inputs for geology or surficial soils, so while there is not a more relevant model for San Diego County that the USGS is aware of (Jason Kean, personal communication, May 10, 2022), there is substantial uncertainty in the volume estimates.

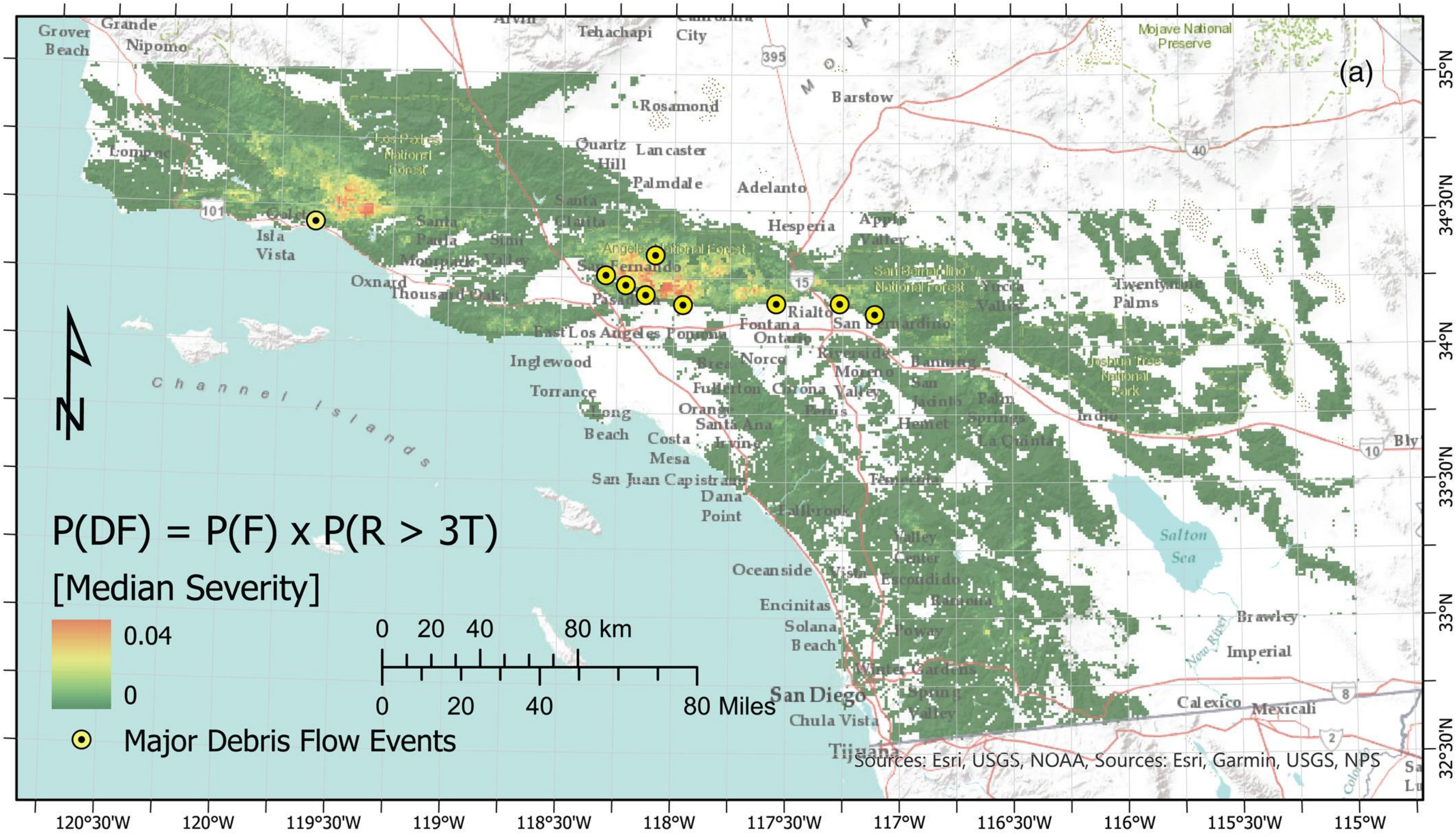


Figure 4-2. Probability of Major Debris Flow Events in Southern California shown with Major Historical Events (Kean & Staley, 2021a)

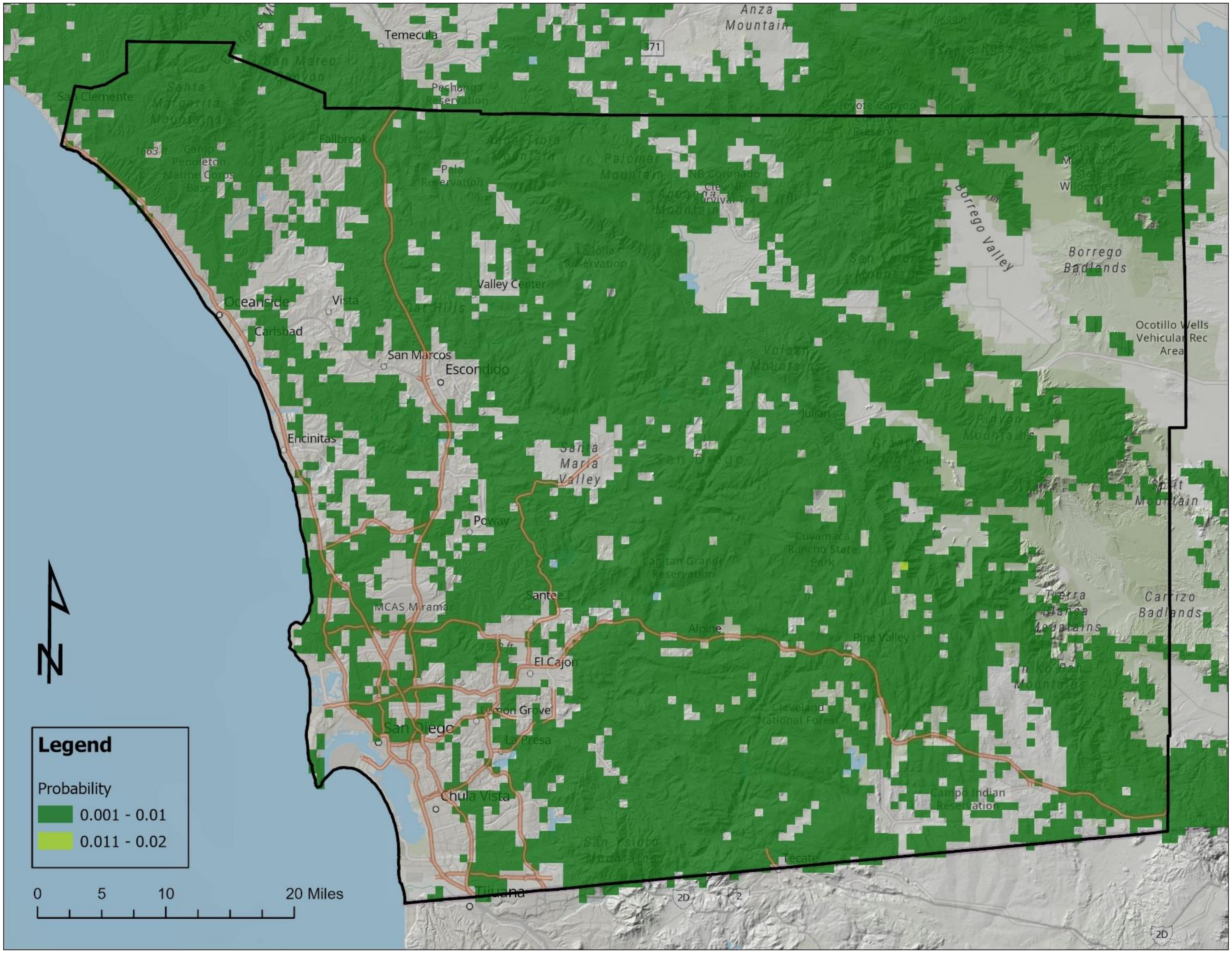


Figure 4-3. Probability of Major Debris Flow Events in San Diego County (Data from Kean & Staley, 2021b)

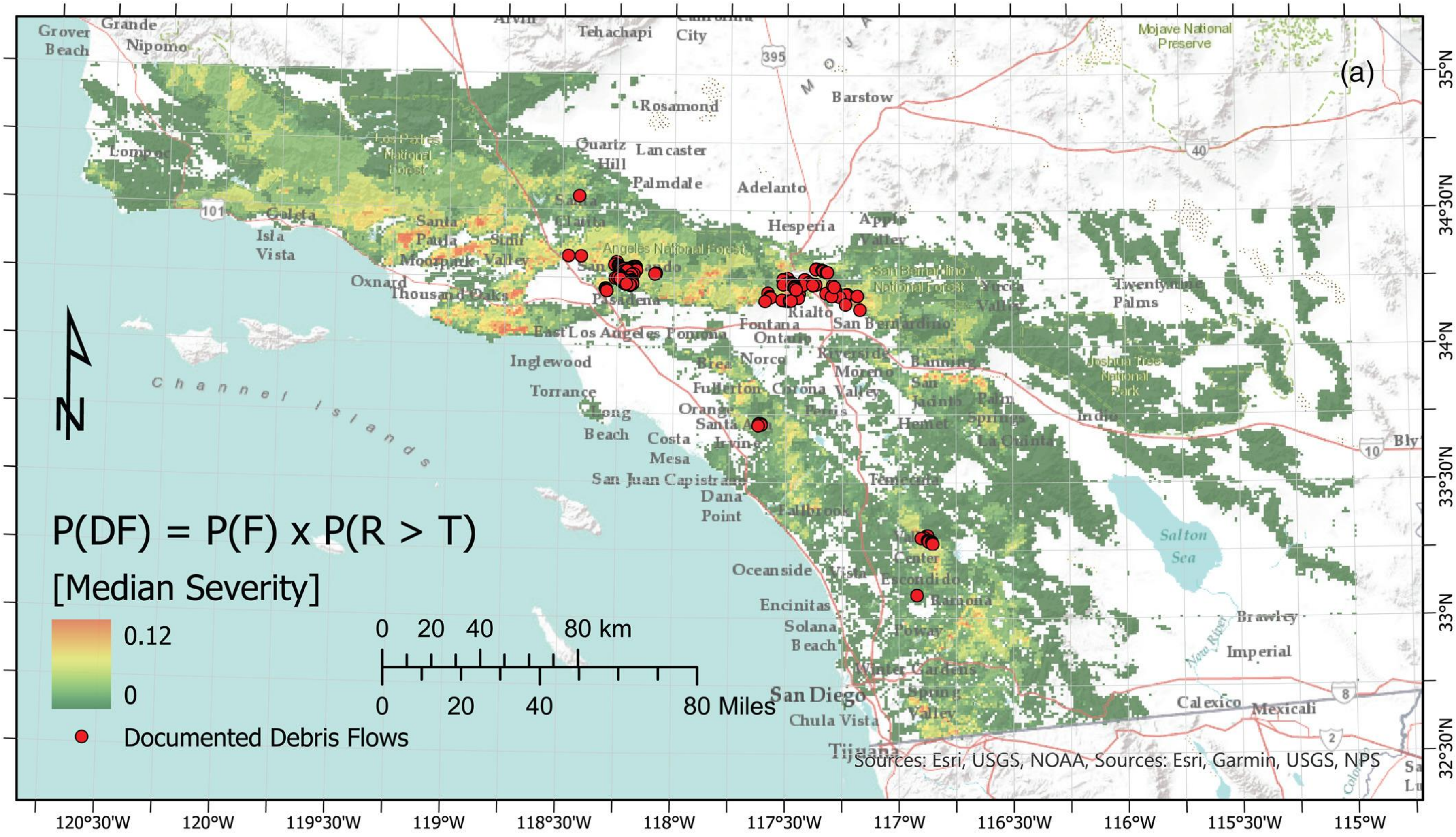


Figure 4-4. Probability of All Debris Flow Events (Major and Minor) in Southern California shown with Historical Events (Kean & Staley, 2021a)

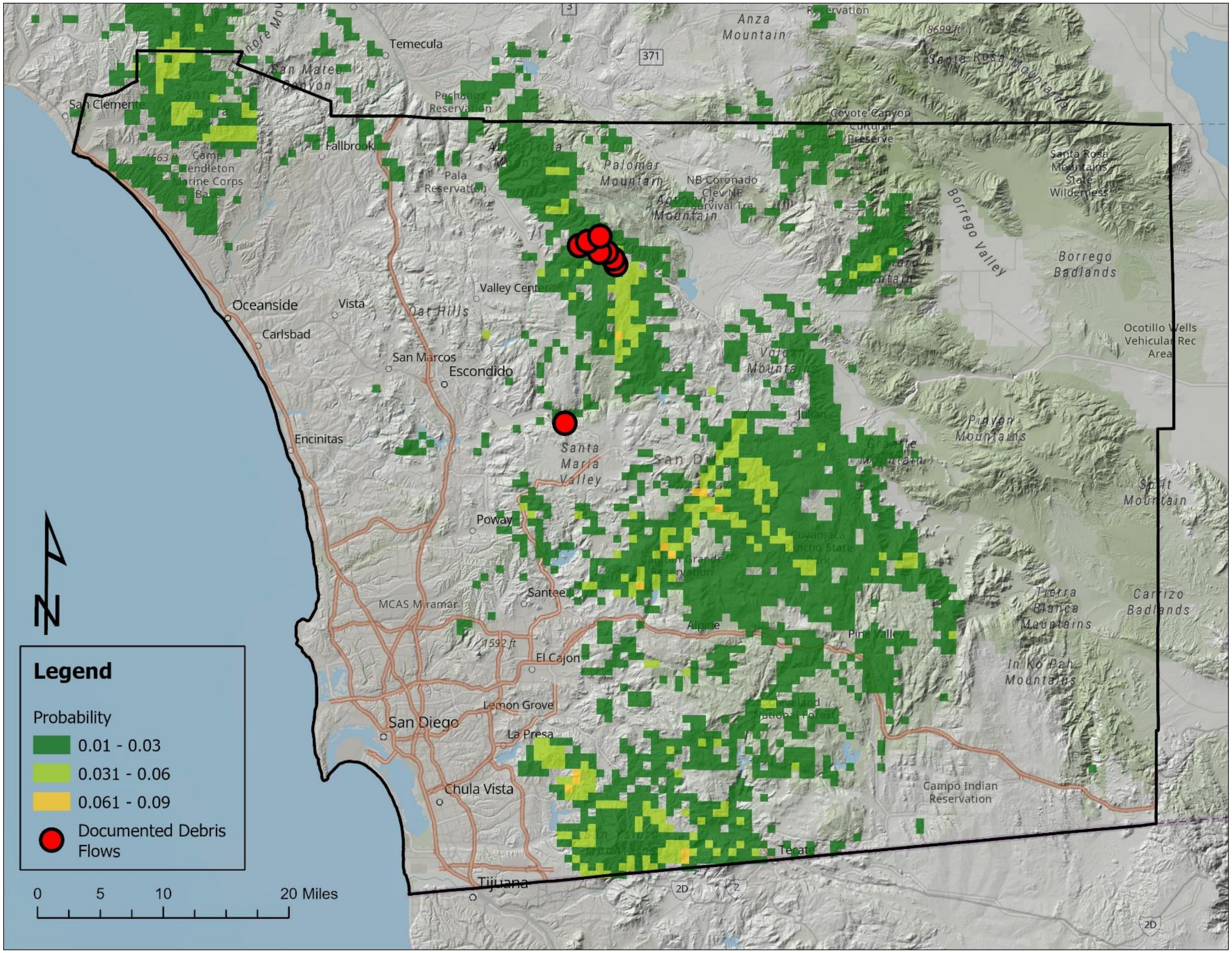


Figure 4-5. Probability of All Debris Flow Events (Major and Minor) in San Diego County (Data from Kean & Staley, 2021b)

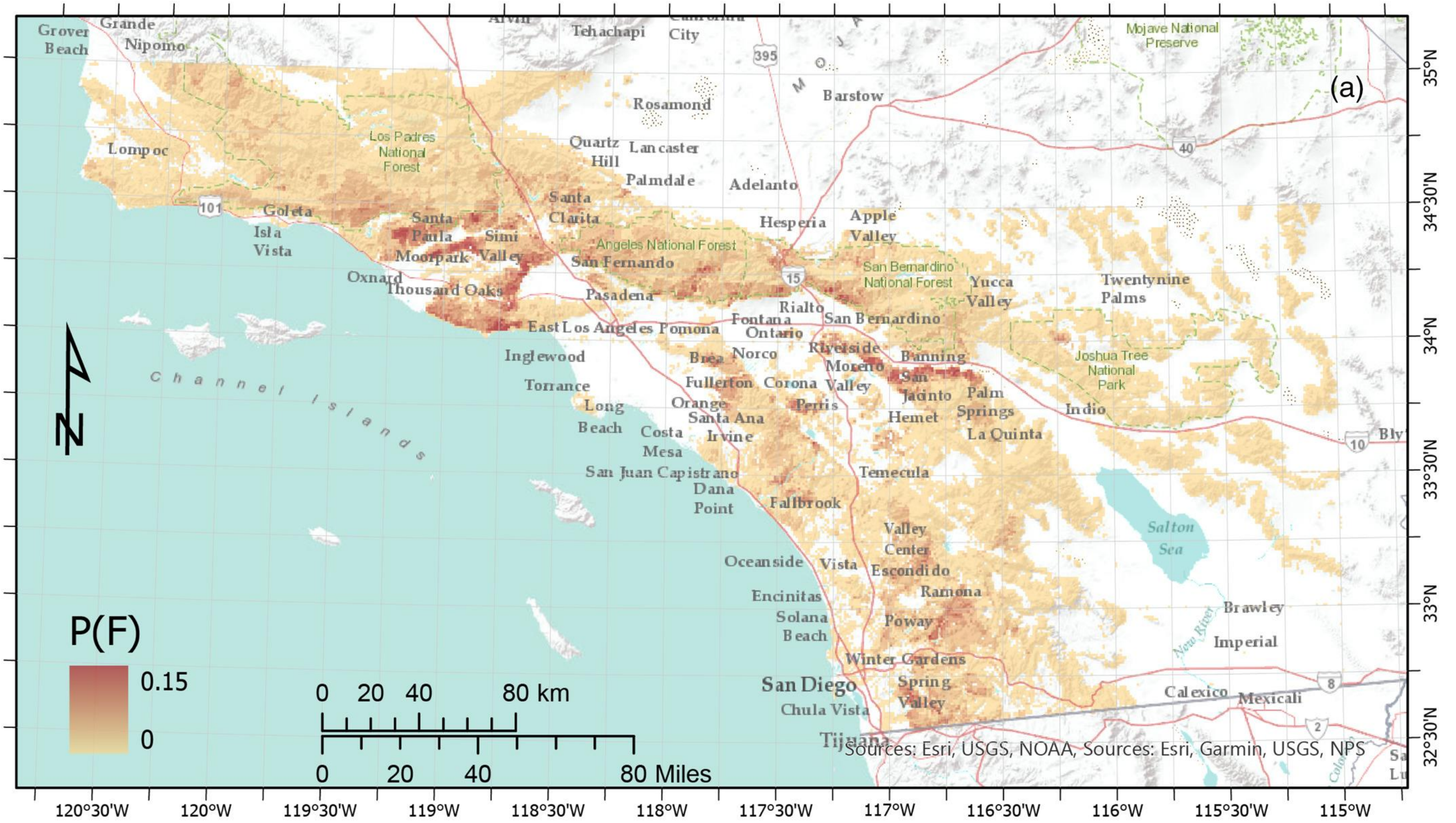


Figure 4-6. Probability of Fire Occurrence (Kean & Staley, 2021a)

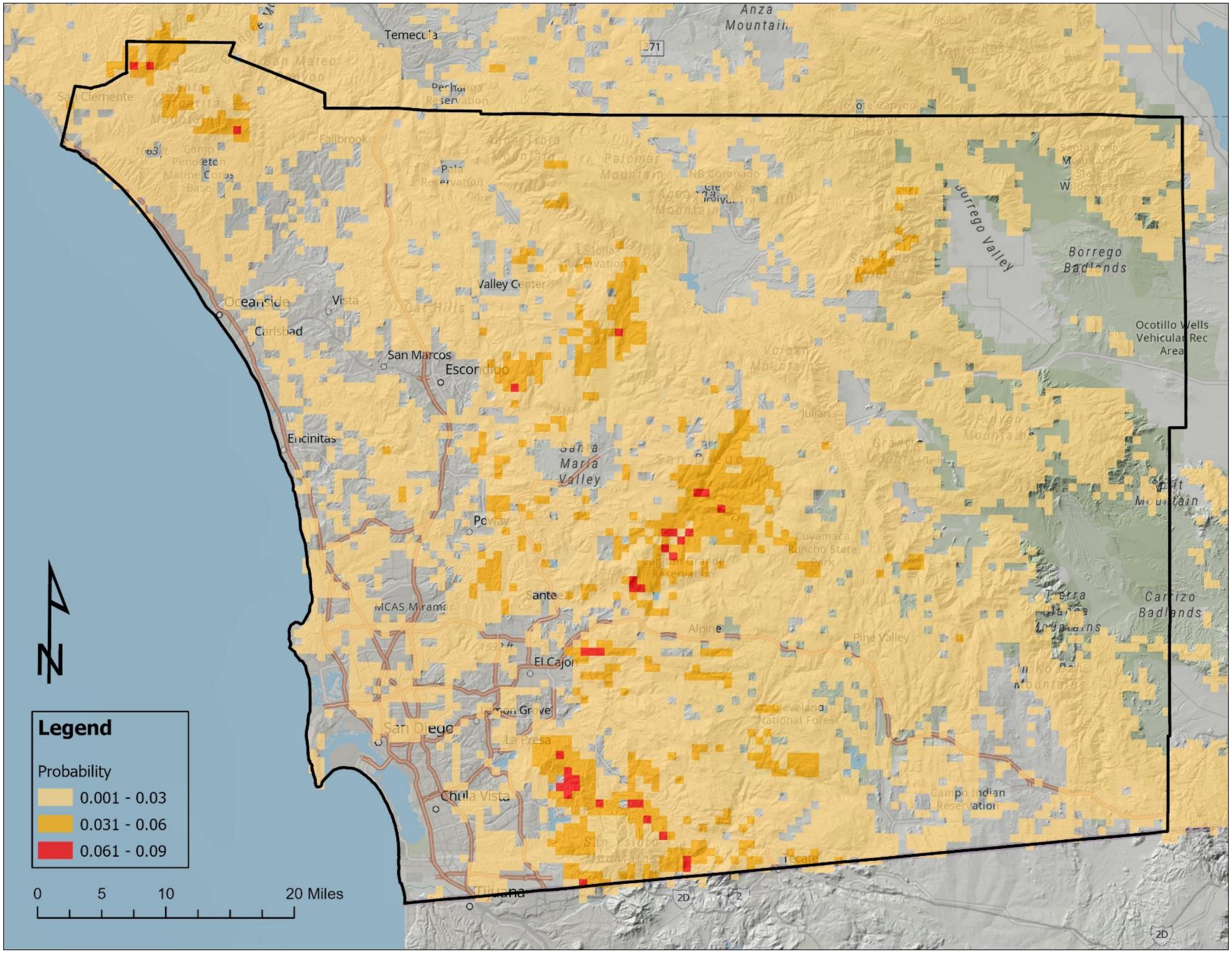


Figure 4-7. Probability of Fire Occurrence in San Diego County (Data from Kean & Staley, 2021b)

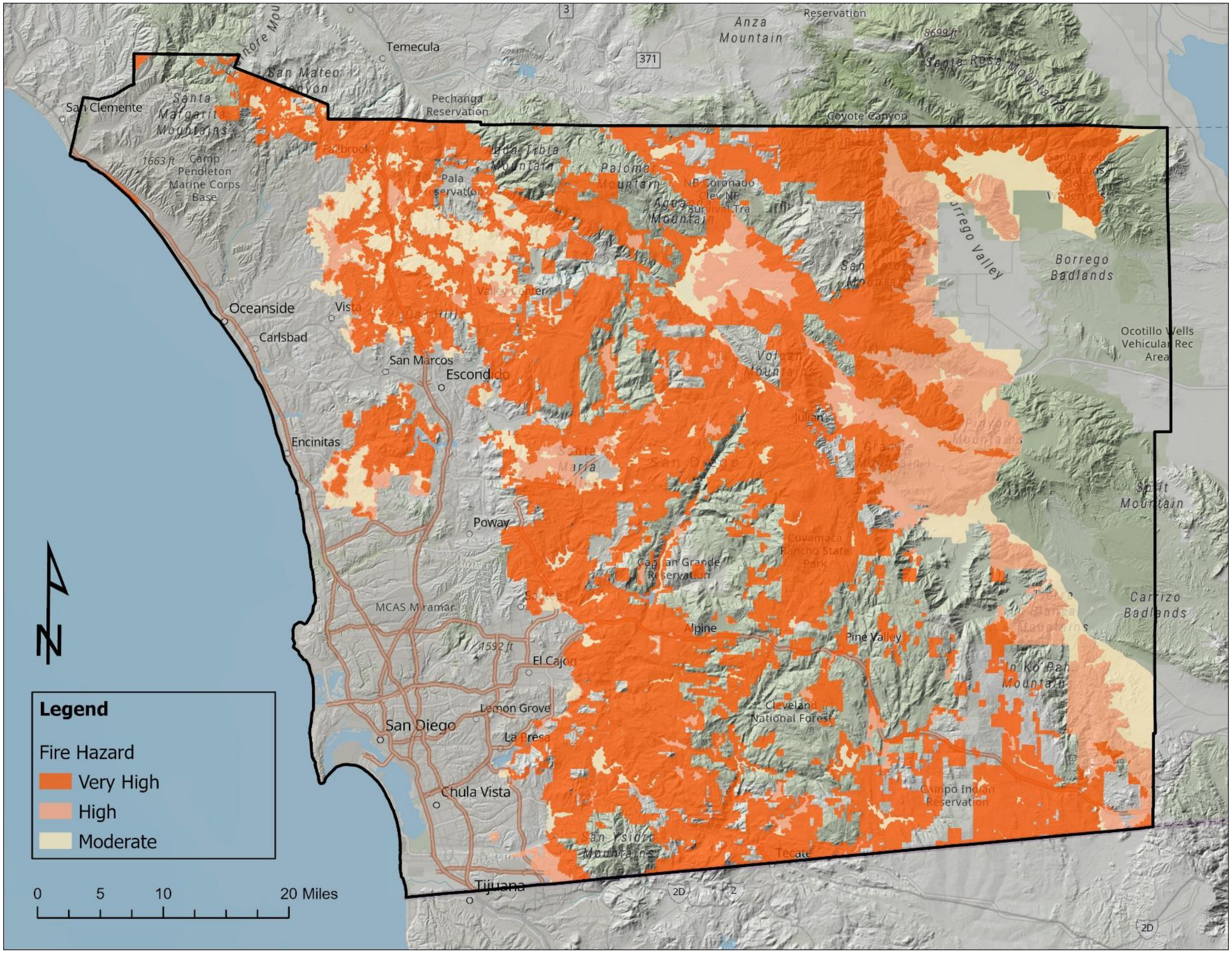


Figure 4-8. Fire Severity Zones for San Diego County (State Responsibility Areas) – CAL FIRE (2022)

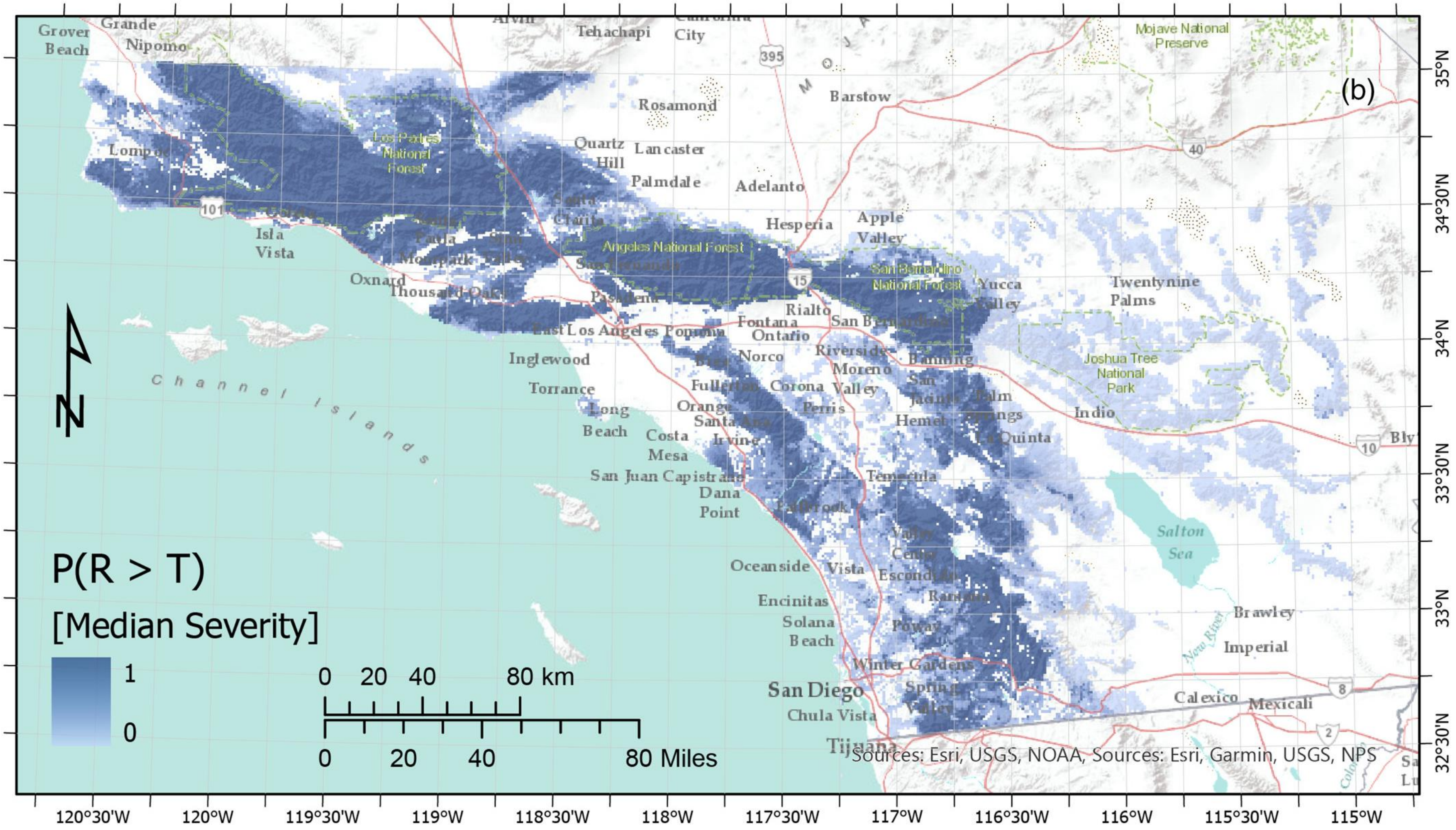


Figure 4-9. Probability of Debris-Flow Triggering Rainfall after Wildfire in Southern California (Kean & Staley, 2021a)

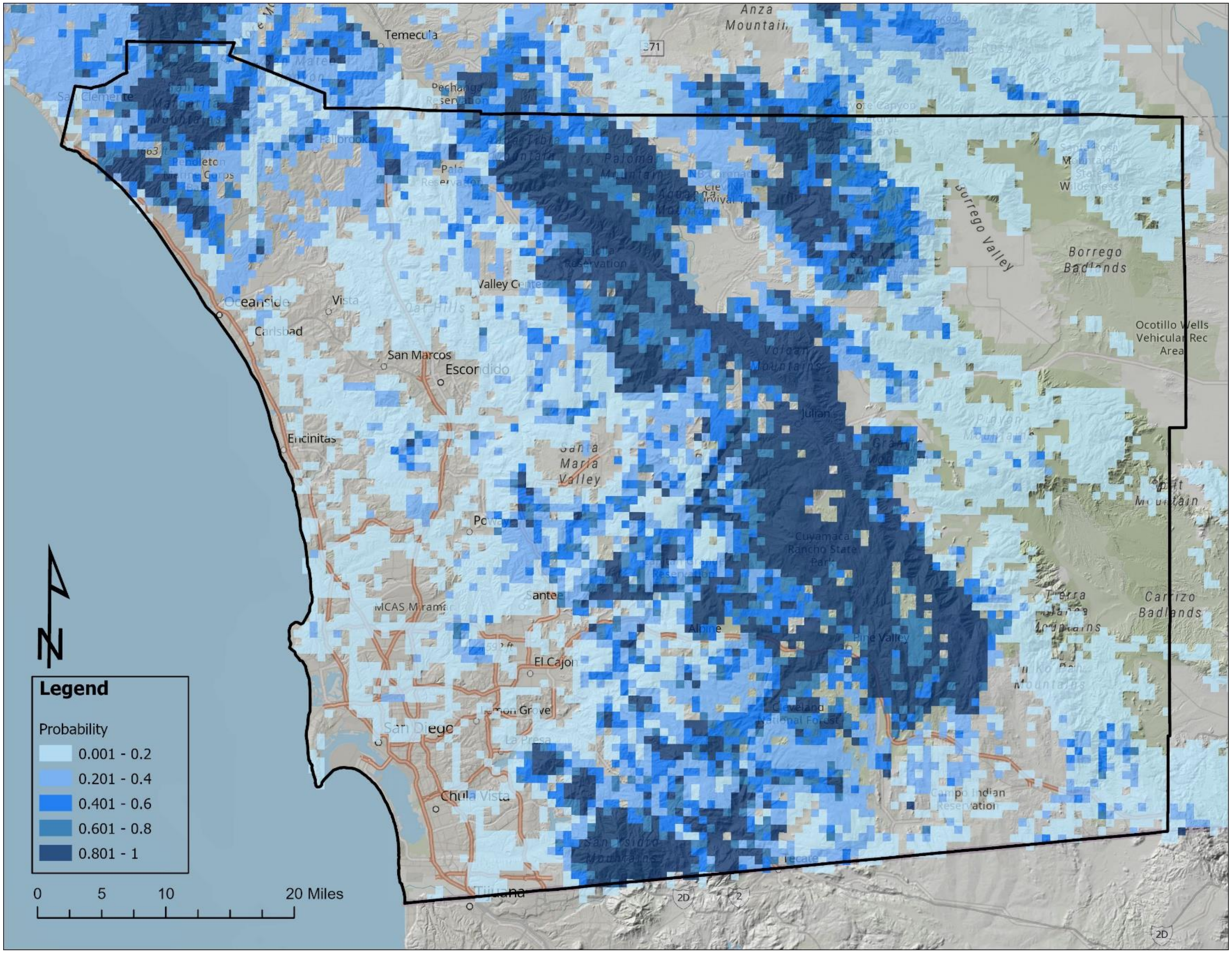


Figure 4-10. Probability of Debris-Flow Triggering Rainfall after Wildfire in San Diego County (Data from Kean & Staley, 2021b)

4.2 Debris Flow Sensitivity to Future Changes in Fire and Rainfall

Annual debris-flow probabilities will likely change in the future if there are changes to fire occurrence, burn severity, and/or rainfall intensity (Kean & Staley, 2021a). Changes to the probability of fire occurrence have a direct impact on debris-flow probability—a 10% increase in fire probability corresponds with a 10% increase in debris-flow probability.

4.2.1 Fire Frequency

In Southern California, the frequency of fire is most related to human sources of ignition, including accidents, arson, and the electric grid. Recently, power companies have begun shutting down parts of the electric grid when fire-conducive weather is forecasted; however, this is a controversial practice, and it is not clear to what extent this policy will continue in the future (Kean & Staley, 2021a).

In terms of climate change, fires exacerbated by Santa Ana winds may decrease in the future due to weaker projected Santa Ana winds (Kean & Staley, 2021a), though some researchers have pointed to a statistically significant increasing trend in winter fire weather frequency in Southern California over the past decades (Guirguis et al., 2022). Fire activity in the fall may increase if evapotranspiration increases due to a warmer climate and the start of the rainy season is delayed. However, the influence of climate change on projected future fire occurrence is weaker in San Diego County and other populated areas throughout Southern California because of the strong influence of humans on fire occurrence (Kean & Staley, 2021a).

4.2.2 Burn Severity

There is a nonlinear relationship between burn severity and debris-flow probability. Burn severity is generally controlled by available fuels, fire weather, climate (over the long term), and topography. While burn severity has increased over much of the western U.S. in recent decades, the trend is less clear in Southern California, where some areas have seen the conversion of frequently burned chaparral to grass; the latter typically experiences less severe burns than chaparral.

Kean and Staley (2021a) performed a sensitivity analysis to evaluate the impact of burn severity on debris-flow probability, comparing results from a 50th percentile burn severity (i.e., the results described in Section 4.1) with an 84th percentile burn severity. For Southern California, debris-flow probability is not particularly sensitive to increases in burn severity from the 50th to 84th percentile, with computed increases of only 1% to 2%.

4.2.3 Rainfall Intensity

While climate prediction models show little change in mean precipitation for Southern California this century, the variability in precipitation is expected to increase, resulting in more extreme rainfall and dry periods (Guirguis et al., 2022). According to projections from Cal-Adapt (2021), rainfall intensity may increase by 18% this century.

Kean and Staley (2021a) performed a sensitivity analysis on the impact of this 18% change in rainfall intensity on debris-flow probability. The increase in rainfall intensity resulted in a substantial increase in the probability of *major* debris flows, but not minor debris flows. This is because the rainfall intensity threshold for any size debris flow is already at or below typical 1-year rainfall intensities under present conditions.

4.3 Regional Geology

The Peninsular Ranges, which include the Santa Ana, San Jacinto, and Laguna Mountains, are generally northwest-oriented and divide San Diego County's coastal-draining watersheds from the eastern deserts (Kean & Staley, 2021a). As shown in Figure 4-11, these ranges are characterized by Jurassic and Cretaceous plutonic, mostly granitic-type rocks, with post-Cretaceous sediments forming only a thin veneer over the plutonic rocks. The older, Mesozoic-era igneous and metamorphic rocks are relatively resistant to erosion (Inman & Jenkins, 1999; California Geological Survey, 2018).

The Peninsular Ranges differ substantially from the nearby Transverse Ranges, particularly in terms of factors related to their erodibility. In their paper, Inman and Jenkins (1999) study the effects of climate change and episodicity on sediment yield in California rivers and note that when the 16 largest (in terms of drainage area) Central and Southern California rivers are aligned in a south-to-north sequence (see Figure 4-13), a clear trend emerges. The four rivers near Point Conception—the westernmost end of the Transverse Ranges—have sediment yields about an order of magnitude greater than those originating in the Peninsular Ranges to the south. In many respects the four rivers are average within the larger sample, with intermediate drainage areas and headwater elevations, and while there are some precipitation differences, the authors conclude, "the variation in the yield of sediment with latitude emphasizes the importance of geological factors in determining erosion along this mountainous collision coast."

To summarize, compared to the Transverse Ranges (Section 2.5.2)—the sediment yield data for which underpin nearly all empirical debris-flow probability and volume equations used in Southern California—the Peninsular Ranges are characterized by the following:

- Lower average elevation
- Reduced topographic relief and hillslope angles
- Less erosion due to older, more-resistant geological formations and stabler surficial soils
- Fewer fault zones
- Significantly less uplift and associated features
- Smaller debris flows
- No major or catastrophic debris flows recently recorded

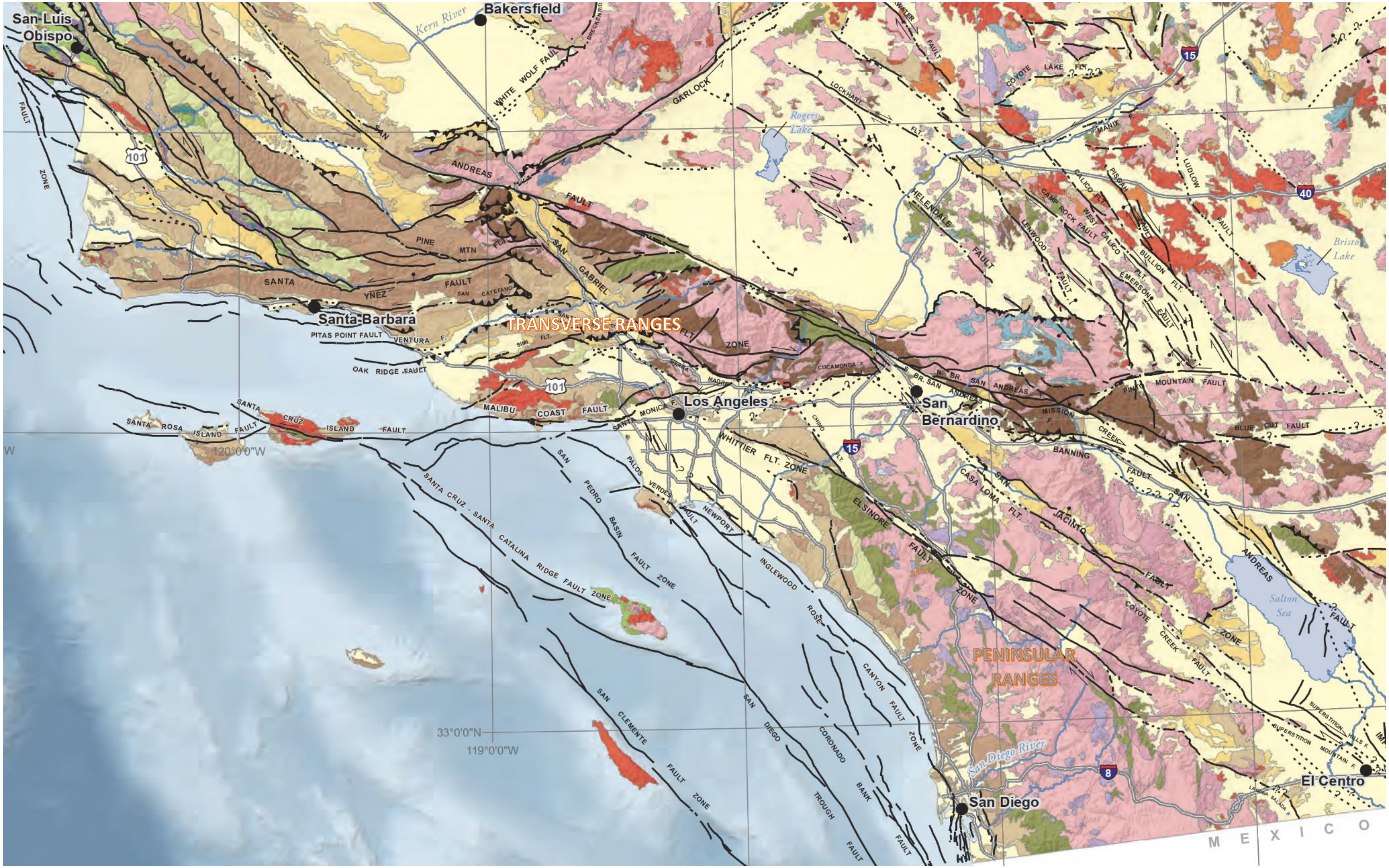


Figure 4-11. California Geology Map, Generally Cropped to Transverse and Peninsular Ranges (modified from California Geological Survey, 2018 and used with permission)

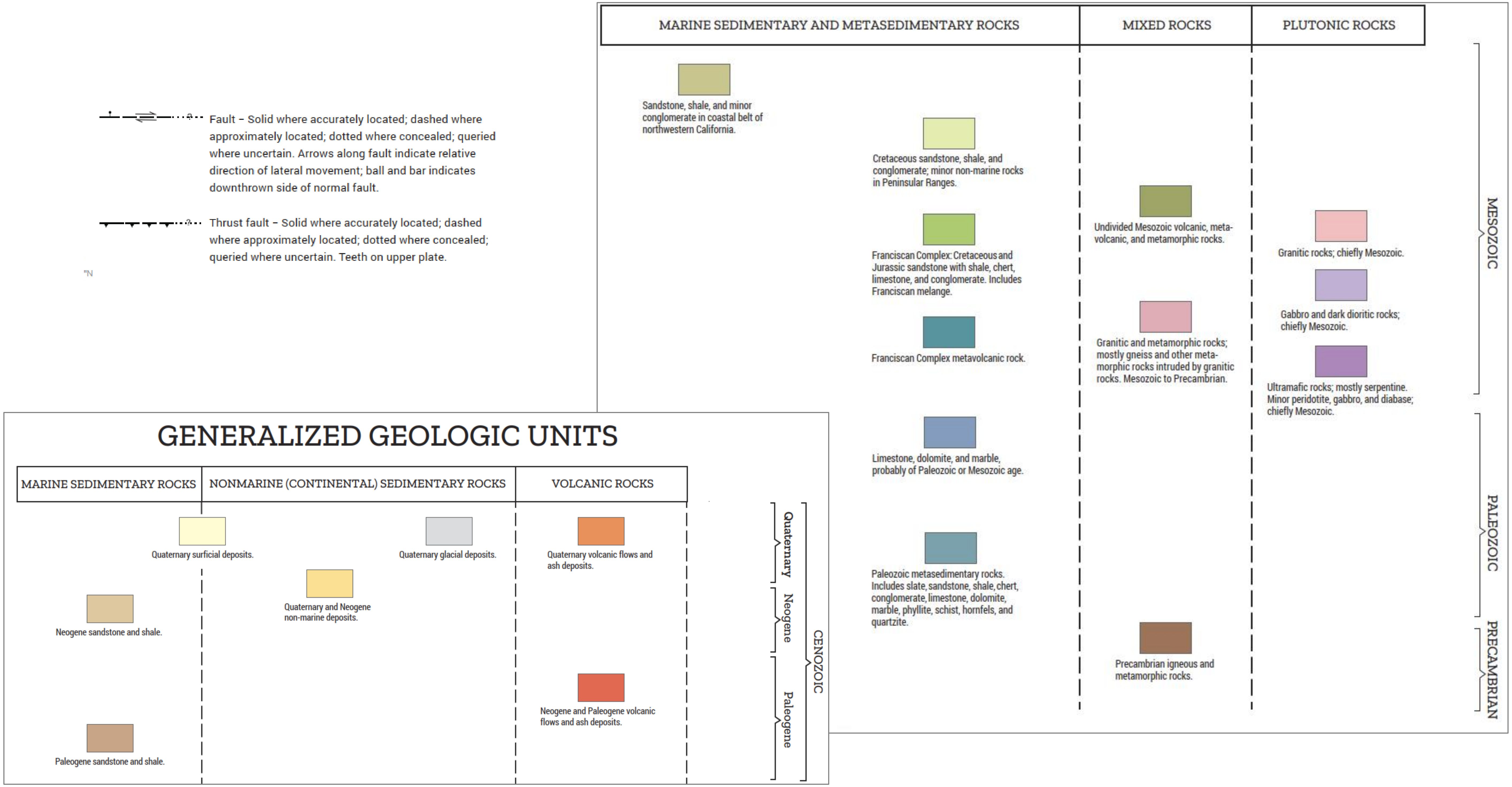


Figure 4-12. California Geology Map Legend (California Geological Survey, 2018, used with permission)

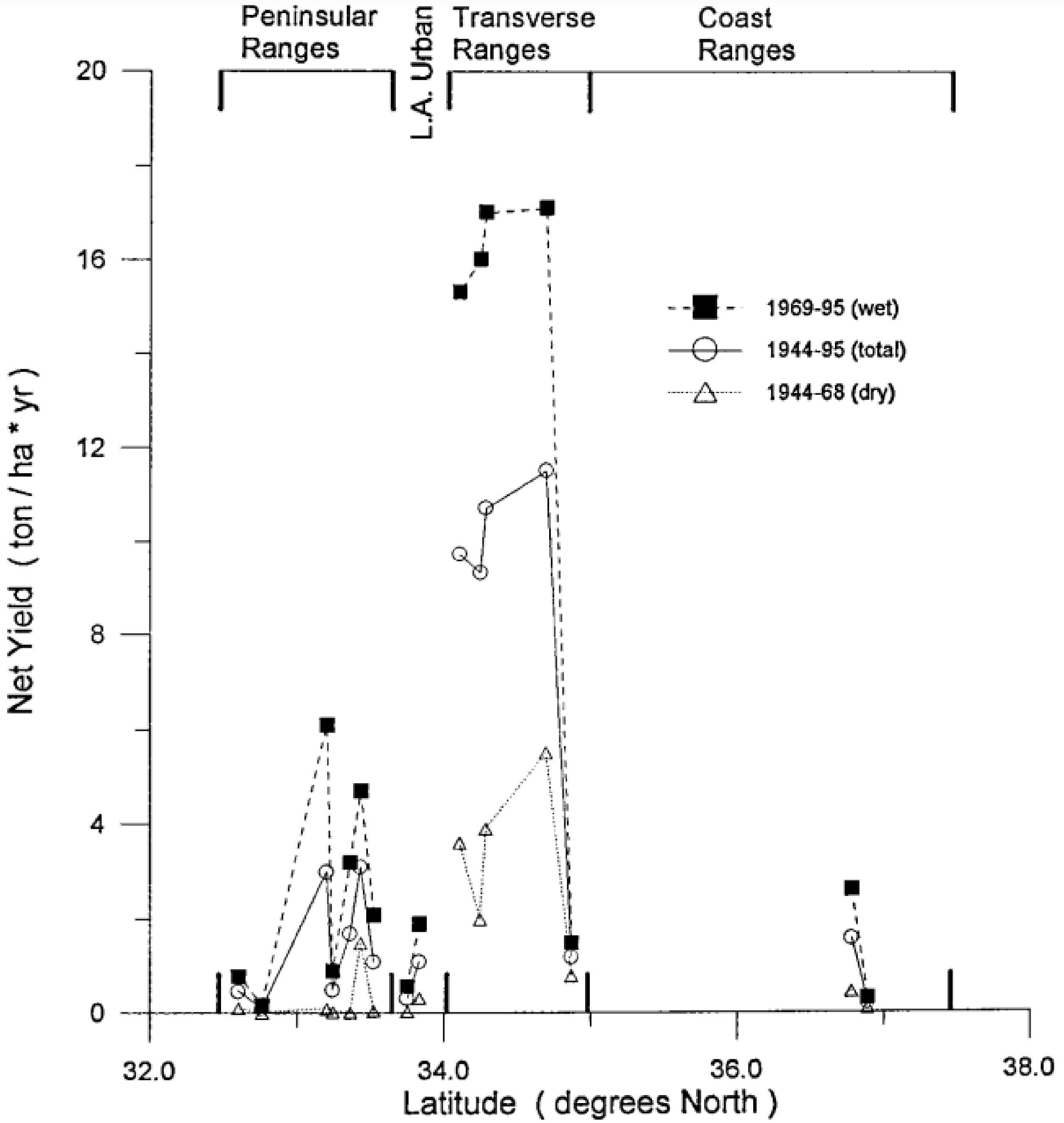


Figure 4-13. Net Sediment Yield vs. Latitude and Province for Southern and Central California Watersheds with Drainage Areas > 300 km^2 (Inman & Jenkins, 1999)

4.4 Alluvial Fans

While alluvial fans are not a primary focus of this report, they frequently pose a sedimentation hazard and so are described in brief here. Alluvial fans are found throughout Southern California, in areas (typically below canyon mouths) where the sediment-carrying capacity of a stream rapidly decreases due to reduced slope and/or an increased flow area (Gusman et al., 2011). Alluvial fans may be formed by normal stream flows, debris flows, or a mix of the two. Alluvial fans formed primarily by debris flows generally have steeper gradients (≥6°) and water-borne sediment concentrations greater than 50% by volume (Silver Jackets, 2020).

Alluvial Fans

(Photo: J. Viducich, October 2022)

Regardless of the type of fan, flood flows in alluvial fan systems are often very flashy and there is substantial uncertainty in flow path and sediment loading predictions due to the availability of highly erodible fine sediment and the large potential for channel avulsion (flow leaving the existing channel). High-velocity, debris-laden flows on alluvial fans are also often triggered by storms following wildfires on and/or above alluvial fans. As development on and near alluvial fans has grown in recent decades, floodplain managers have recognized the need to evaluate the potential behavior of alluvial fans during floods and to develop the flood protection measures required for protection of life and property (Alluvial Fan Task Force, 2010). In San Diego County, development on alluvial fans is regulated by the County's Flood Damage Prevention Ordinance and Building Code, the State of California building codes, and the Code of Federal Regulations (CFR).

4.5 Landslides

The USGS has compiled and mapped historic landslides throughout the U.S. (Jones et al., 2019). Figure 4-14 shows these historic landslides within San Diego County. One of the main limitations of the landslide data for use in the current study is that the dataset includes old landslides that have since been regraded and/or developed. While landslides can supply substantial sediment/debris to channels, and that excess sediment/debris may be mobilized by a subsequent large storm event, the potential for debris-flow events, as described in previous sections, is a better indicator of sediment/debris risk than is the landslide mapping.

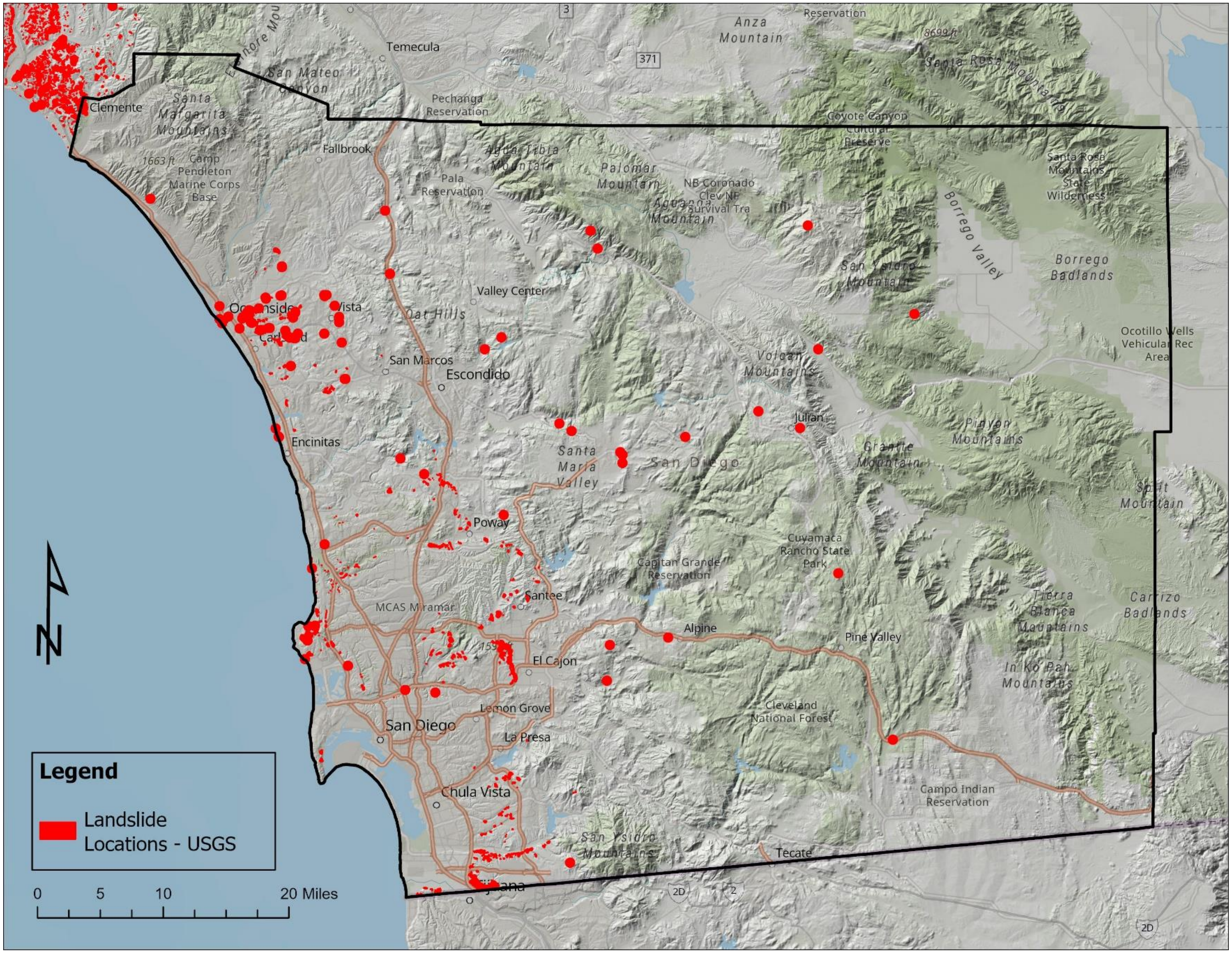


Figure 4-14. Historic Landslides in San Diego County (Jones et al., 2019)

5 RECOMMENDATIONS FOR SAN DIEGO COUNTY

Based on the findings of this study, the authors recommend the following approaches in San Diego County.

5.1 Case-by-case Approach to Sediment Yield / Bulking in High-Risk Areas

While San Diego County is frequently included in regional sediment hazard assessments and methodologies, this study highlights the reality that San Diego's watersheds are generally less erosive than those of the Transverse Ranges (for the reasons given in Section 4.3), and there is substantial variability even within the County. As described in Section 2.3.5, sediment bulking factors are not typically applied to normal streamflows, and instead are applied when hyperconcentrated or debris flows are expected.

In California, bulking factors are typically applied to design discharges for facilities with a) watersheds in mountainous regions generally subject to fire and subsequent erosion, or b) arid regions when the facility is near an alluvial fan (Caltrans, 2020). For San Diego County, this means that many drainage basins are not expected to yield enough sediment during the 100-year design event to warrant the application of sediment bulking factors under normal conditions (that is, not immediately following a wildfire, when increased sediment hazards may pose elevated risks).

To this end, we recommend that sediment/debris hazards under normal conditions only be evaluated for new flood control infrastructure design projects when the project is located within or immediately downstream of selected areas with elevated risks, and that appropriate methodologies be used to plan for sediment loads on a case-by-case basis.

5.1.1 Step 1: Review Sediment/Debris Hazard Map to Identify Known Risk

Two primary types of sediment/debris hazards pose likely risks to flood control infrastructure in San Diego County: debris flows and alluvial fans. The authors developed a new map outlining these high-risk sediment/debris hazard areas in San Diego County, presented in Appendix D. If a new project is not located within or immediately downstream of an identified high-risk sediment/debris hazard area, we do not recommend that sediment/debris retention capacity or flow bulking be required for normal conditions at this time. For new projects located within identified areas of risk, we recommend that users proceed to Step 2.

The following sections describe the two types of identified sediment/debris hazards and the data sources used to develop the final sediment/debris hazard map.

5.1.1.1 DEBRIS FLOWS

Areas identified by the USGS (Kean & Staley, 2021b) as having a moderate-to-high probability of occurrence of small or major debris flows should be assessed for potential sediment/debris mitigation requirements. These are shown in Figure 5-1, and a photo of an example watershed, located near Garnet Peak in the Laguna Mountains, is shown in Figure 5-2.

To develop this map, polygons were digitized around the 1 km^2 cells with at least a 1% annual chance (equivalent to a 100-year event) of a minor debris flow and/or at least a 0.5% annual chance (equivalent to a 200-year event) of a major debris flow. Digitized hazard areas generally follow Hydrologic Unit Code (HUC)-12 watershed boundaries to reflect the potential downstream sediment impacts of debris flows within a watershed. A small number of isolated 1 km^2 cells are omitted from the overall hazard polygons in the interest of simplicity and due to the relatively low hazard associated with these; none contain potential major debris flows. Digitized hazard areas mainly include mountainous watersheds in the center of the County and watersheds near Camp Pendleton in the northwest portion of the County.

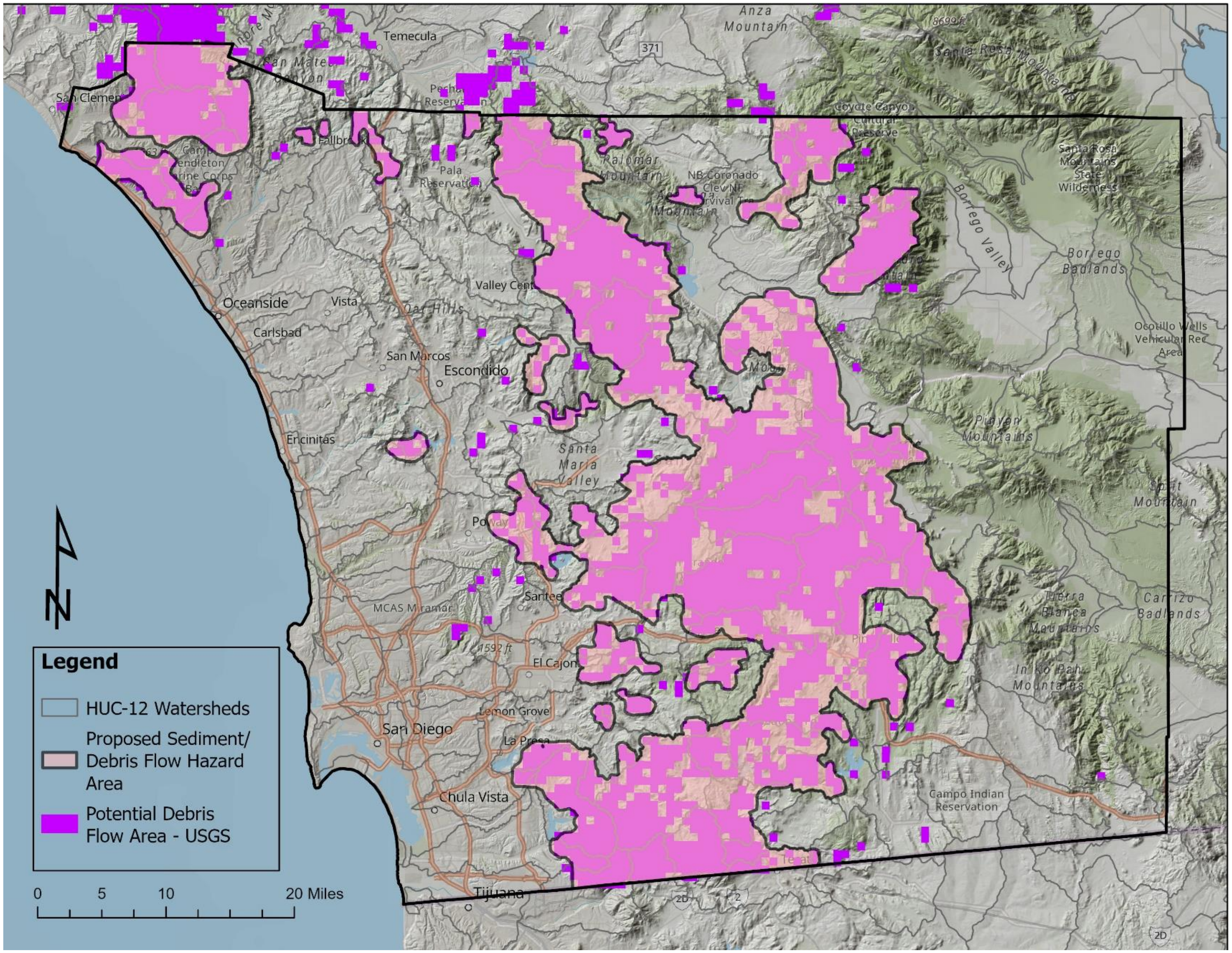


Figure 5-1. Digitized sediment/debris hazard regions associated with areas having at least 1% annual chance of minor debris flows or at least 0.5% annual chance of major debris flows, based on USGS data (Kean & Staley, 2021b).

Figure 5-2. This June 2022 photo shows a small watershed in the Laguna Mountains with at least a 1% annual chance of debris flows, based on USGS data (Photo: J. Viducich, River Focus).

5.1.1.2 ALLUVIAL FANS

This study recommends that all projects located on desert alluvial fan areas be evaluated for potential sediment/debris impacts. These areas are shown in Figure 5-3 and represent data from two studies, described below.[5]

In 2013, the Desert Research Institute performed detailed mapping of active and inactive alluvial fans near Borrego Springs for the County of San Diego, as shown in Appendix E (Bacon, Miller, & French, 2013). The authors note that while channel patterns on inactive areas of alluvial fans are relatively stable on an engineering timescale, they can be subject to flooding if located adjacent to and not elevated above active areas when avulsion occurs upstream during higher flows. For this reason, Figure 5-3 incorporates both the active and inactive fan areas. Data provided by the Desert Research Institute in Appendix D of their report (Bacon, Miller, & French, 2013) are available in vector (polygon) format.

In 2012, the California Geological Survey (CGS) updated Special Report 217 (Bedrossian et al., 2012) to include a GIS-based compilation of geologic maps characterizing the extent and types of alluvial fan deposits in Southern California. While detailed data are not yet available for all parts of San Diego County—for example, the Borrego Valley Quadrangle is not included in the revised CGS compilation—the project also produced a simplified map of areas that *may* include alluvial fans throughout the entire 10-county region. To develop the map, CGS identified the general distribution of areas underlain by Quaternary-age sediment less than 2 million years old, then subdivided those into areas that may contain alluvial fans (Qs1) and topographically low areas including playa lakes and coastal lowlands (Qs2). Data are available in vector (polygon) format from the Special Report 217 webpage (Bedrossian et al., 2012).

West of the Peninsular Ranges, Qs1 alluvial deposits are typically found in developed areas or in streambeds and so are not primary areas of concern. All other Qs1 regions identified in Special Report 217 and located east of the Peninsular Ranges are included in Figure 5-3, with the exception of the Borrego Springs area, where alluvial fan data from the Desert Research Institute are used.

Given that areas with recent deposition (Late Holocene time, within the past 500 years) are the most likely to be areas of flooding and deposition in the future, and older alluvial fan deposits are likely lower risk (Bedrossian et al., 2012), we recommend that the alluvial fan sediment/debris hazard map be updated as additional detailed information become available.

5.1.2 Step 2: Identify Whether Planned Infrastructure is at Risk

If a new project is planned in an identified sediment/debris hazard region, the next recommended step is to evaluate whether values are truly at risk, whether the value is critical, and whether the cost of repair or replacement exceeds the likely cost of mitigation.

For example, if a drainage basin is large and the planned infrastructure is in the lower-gradient portion of the reach, beyond the anticipated runout of sediment/debris, debris flows in upper reaches may have minimal impact and mitigation may not be required.

---

[5] The potential alluvial fan areas identified in the study are not intended to delineate alluvial fans for County of San Diego and/or FEMA floodplain management purposes.

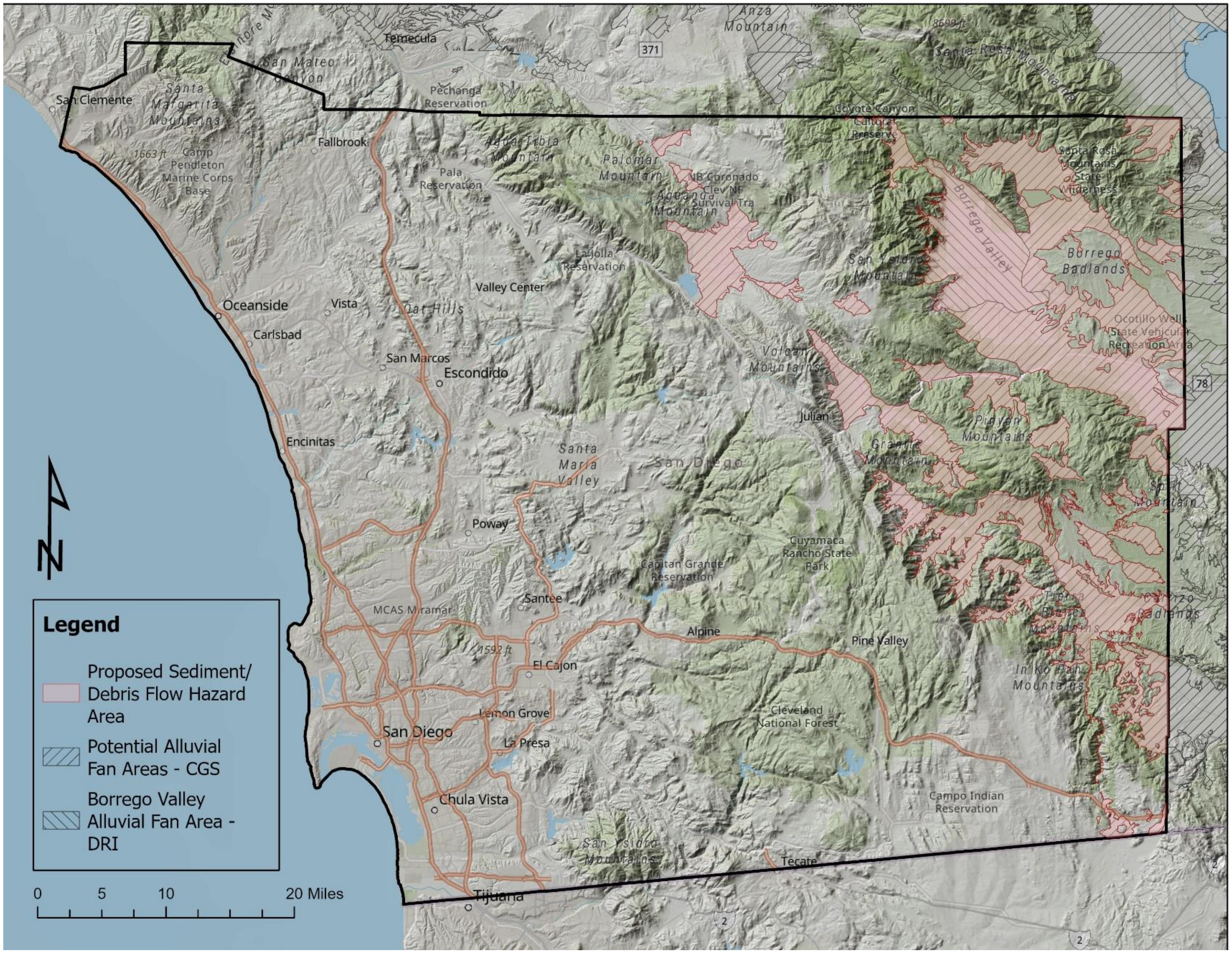


Figure 5-3. Sediment hazard regions associated with desert areas that may contain alluvial fans, based on data from the CGS Special Report 217 (Bedrossian et al., 2012) and the Desert Research Institute (Bacon, Miller, & French, 2013).

This study recommends that projects planned near channels with slopes of 2 percent or less not require planning for upstream sediment mitigation, based on the survey of findings presented in Gusman et al. (2011), and that detailed analysis (e.g., modeling) by a qualified geologist or engineer may be used to evaluate likely debris flow runout location(s) upstream of a project planned near channels with a slope greater than 2 percent.

Also, if the risk of damage to infrastructure is low (for example, a structure planned outside of the floodplain) or the anticipated cost of repair or replacement of a non-critical values-at-risk location is low relative to the cost of hazard mitigation, mitigation may not be required.

5.1.3 Step 3: Select Appropriate Mitigation Option(s)

Generally, sediment/debris hazards should be mitigated using one or both of two options: sediment/debris basins and/or the application of a sediment bulking factor to increase the flow magnitude for which conveyance structures are designed.

5.1.3.1 SEDIMENT/DEBRIS BASINS

To avoid the need for downstream flow bulking (or to reduce the bulking factor required), sediment/debris basins can be designed at or near canyon outlets (i.e., not on an alluvial fan or valley fill area) and sized with sufficient capacity and appropriate hydraulics to capture and store the estimated 100-year sediment/debris event while allowing storm flows to pass.

It is important to note that the County’s Hydromodification and Critical Coarse Sediment Yield Area regulations may restrict whether a sediment/debris basin can be implemented at a given project location. Users should refer to Appendix H of the County of San Diego BMP Design Manual to identify potential critical coarse sediment yield areas (County of San Diego, 2020). In restricting the downstream flow of sediment, a basin can discharge flow with low concentrations of sediment (known as “hungry” water), which can cause erosion and scour downstream of the basin. These concerns need to be addressed in the basin planning process.

If a sediment/debris basin is allowed and warranted, the 100-year sediment/debris yield at the selected basin location should be estimated by performing a coincident frequency analysis for fire and precipitation or runoff and applying the Los Angeles District Method. (See Chapter 6 of Gatwood et al. (2000) for theory and instructions.)

Data required for the Los Angeles District Method are summarized below:

- Historic fire perimeter data for the period 1950-2021 are currently available from CAL FIRE (https://frap.fire.ca.gov/mapping/gis-data/)
- Atlas 14 precipitation frequency estimates are available from the National Oceanic and Atmospheric Administration Precipitation Frequency Data Server (PFDS) (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=ca)
- Unit peak runoff computed using current San Diego County Hydrology Manual methods.

- The USACE Hydrologic Engineering Center - Statistical Software Package (HEC-SSP; https://www.hec.usace.army.mil/software/hec-ssp/) can be used to perform the coincident frequency analysis.

Due to the differences between the San Diego Peninsular Ranges and the Transverse Ranges where the Los Angeles District Method was developed, an appropriate A-T Factor must be identified to reflect what in most cases will be less-erodible watersheds. As previously noted, in Appendix B of their report, Gatwood et al. (2000) describe four techniques for determining an appropriate A-T Factor. We anticipate the fourth method will be used in most cases in San Diego County, and the A-T Factor will be recommended by a qualified geologist or engineer, based on a desk study, field observations, and the provided guide in Table B-1 of Gatwood et al. (2000).

Finally, if a sediment/debris basin is to be used to mitigate sediment/debris hazards, a maintenance plan must be established to ensure the basin is regularly emptied and its design capacity restored. Ideally, sediment/debris will be removed after each depositional event and the volume recorded to support the development of San Diego County-specific datasets useful for improving sediment/debris methods for local watersheds.

5.1.3.2 FLOOD CONVEYANCE INFRASTRUCTURE

In some cases, it may not be feasible to construct a sediment/debris basin at the mouth of a canyon upstream of a project location, or a planned sediment/debris basin may not have sufficient capacity to capture and store the design sediment/debris yield. In these cases, downstream flood conveyance infrastructure (e.g., engineered channels, culverts, etc.) must be sized to convey the bulked peak flow.

Flow bulking may be done using either of two approaches:

1. First, the 100-year sediment/debris yield at the upstream end of the flood conveyance system can be estimated using the same method described in the previous section, then the total sediment volume can be distributed throughout the design 100-year clear-water hydrograph using Equation 3.1 to identify the peak bulked flow.[6] (For smaller watersheds where a hydrograph is not available, a conservative bulking factor can be used. See Approach #2 below.)

   We recommend that the bulking exponent, *n*, initially be fixed at 3, based on Gusman et al. (2011) and the approach currently used in Ventura County; however, future study should be made to support the conservatism of the assumption that the sediment and water flow contributions always peak at the same time and that the *n* bulking exponent value should be fixed at a given value (e.g., 3).

---

[6] If a sediment/debris basin is used to capture some portion of the 100-year design sediment/debris volume before flow enters the flood conveyance system, the remaining sediment/debris volume can be used to compute the bulking factor. Engineering judgment must be used when distributing the sediment volume throughout the flow hydrograph, however, due to the decreased loading at the start of the hydrograph.

The computed bulking factor (the ratio of the bulked discharge to the clear-water discharge) should be at minimum 1.2 and maximum 1.5. Bulking factors are expected to be at the lower end for watersheds larger than 3 mi^2.

These values are based on the analysis and design bulking factors for Ventura County presented in Gusman et al. (2011) and Table 3-2. Note that the upper end for small watersheds recommended here (BF = 1.5) is slightly smaller than the 1.6 presented in Table 3-2. This is justified for two reasons: San Diego County watersheds are generally expected to have lower sediment yields than the Transverse Ranges in Ventura County, and except for a single historical sedimentation event in Ventura County, all others recorded there had bulking factors less than 1.5.

2. If preferred, a conservative bulking factor may be adopted without additional analysis:

    1.2 for drainage areas > 3 mi^2

    1.5 for drainage areas ≤ 3 mi^2

Regardless of which method is used for flow bulking, an accompanying sediment transport analysis should be performed to ensure that the flood conveyance system can effectively transport the design sediment load. From a hydrological perspective, sediment and water together comprise a single flow with shared properties, while from a hydraulics perspective, channels may aggrade or degrade based on their transport capacity and the sediment loading. So, a channel and culvert sized to convey a larger bulked flow must also be designed such that supplied sediment and debris are effectively conveyed through the culvert and do not deposit upstream (where they might limit channel capacity). For more information on analyzing sediment transport, see Section 5.11 of the San Diego County Hydraulic Design Manual (County of San Diego, 2014).

5.2 Post-fire Emergency Assessment

Fire often dramatically changes sediment and flood risk calculations. A watershed with relatively low risk under normal conditions—possibly, even one that would not generally require sediment/debris hazard mitigation based on the recommendations of this study—may pose immediate risks to critical infrastructure immediately after a fire. Because of this, a similar, but different set of procedures should be used to address post-fire sediment/debris and flood hazards, as outlined in the following steps. For this study, the post-fire period is defined as up to 10 years after a wildfire.

5.2.1 Step 1: Refer to BAER and WERT Analyses (if Available)

Defer to guidance provided by Federal BAER and State WERT assessments for areas where they are available. As described in Section 3.7, this will generally include large fires whose effects pose risks to critical values.

5.2.2 Step 2: Identify Critical Values and Basin Outlets (Immediately After Small Fires and for Medium-Term Design)

BAER/WERT assessments are not generally made for small fires or portions of fires outside of the programs' responsibility areas, and generally focus on the immediate, emergency period following fires. We recommend that similar emergency assessments be made for smaller fires, and that sediment hazards be evaluated for new developments planned in or immediately downstream of burn areas during the period 2-10 years after fires.

As with BAER/WERT analyses, post-fire assessments performed by the County or other local jurisdictions should begin by identifying sites with values at risk and defining corresponding basin outlets.

If there are no critical values at risk immediately following a fire, then it may not be necessary to continue with the emergency assessment of short-term hazards. However, while the risk of some hazards, like debris flows, diminishes in the first two years following a fire, elevated sediment loading often persists for a longer period and so should be accounted for in new development planned in or immediately downstream of an area burned in the previous 10 years. Historic fire perimeter data (from 1950 to 2021) are available from the CAL FIRE website: https://frap.fire.ca.gov/mapping/gis-data/.

In these cases, the new development should be treated as the critical value, and special post-fire analyses should be used to assess hazards. If the new development is also located in an identified sediment/debris hazard area, both the general design and special post-fire sediment analyses should be performed, and the larger sediment yield/bulking factor used for design.

5.2.3 Step 3: Perform Analyses, Select, and Size Appropriate Mitigation Option(s)

Emergency assessments for short-term mitigation can generally be made using guidance presented in the Flood After Fire Toolkit (Silver Jackets, 2020); the methods for evaluating post-fire hydrology, debris flows, and surface erosion hazards are summarized in Section 3.7.3 and discussed in brief in the following sections. Methods for evaluating medium-term hazards are also described below.

The full suite of emergency post-fire runoff and sediment hazard mitigation options (e.g., hydromulching) are beyond the scope of this study; here, we assume that computed post-fire runoff and sediment from an untreated watershed arrive at the project site unimpeded. The same general principles outlined in Section 5.1.3 apply, in terms of estimating a sediment yield that must either be retained in a sediment/debris basin and/or distributed throughout a design hydrograph and conveyed through an adequately sized drainage system. Here, the primary difference is the increase in the post-fire runoff, which also must be accounted for in post-fire design.

5.2.3.1 POST-FIRE HYDROLOGY

Post-fire adjustments to clear-water hydrology can be made using two types of approaches:

1. Use one or more simple, empirical methods to rapidly estimate post-fire peak flow. Due to the limited data on which available empirical relationships are based, this approach should mainly be used for emergency assessments, and multiple methods

should be used whenever time and available data permit. Examples include RCS lookup tables (Rowe et al., 1949 & 1954), Moody (2012), USGS regional regression equations using the flow modifier method (Foltz et al., 2009), and Wilder et al. (2020).

2. Develop or update a hydrologic watershed model using appropriate model parameters to represent the altered watershed characteristics. This option is likely most appropriate for identifying and refining peak flow estimates in the months and years following a fire, unless a calibrated model already exists at the time of the fire. The U.S. Department of Agriculture's Hydrology Technical Note No. 4 (USDA, 2016) is an excellent technical resource for hydrologic modelers simulating burned watersheds. Selecting appropriate model parameters will usually require information about soil burn severity, which, as described in Section 3.7.3, typically begins with the development of a BARC map. For small fires that do not receive BAER/WERT study, San Diego County or other jurisdictions can contact the USFS or DOI for imagery and BARC support, which is generally available on a cost-reimbursable basis. (See https://burnseverity.cr.usgs.gov/baer/contact-baer for more information.)

5.2.3.2 POST-FIRE SEDIMENT YIELDS DUE TO DEBRIS FLOWS AND MEDIUM-TERM SEDIMENT-LADEN FLOWS

Post-fire debris flow likelihood is likely best assessed using Staley et al. (2017) and a conservative computation of post-fire debris flow volume is likely best assessed using either Gartner et al. (2014) or Gatwood et al. (2000), depending on data availability. (Note that while the Los Angeles District Method can be applied in a coincident frequency analysis for general design during normal conditions, it can also be used at a specific time post-fire to predict the debris flow volume resulting from an *n*-year flood given the watershed burn condition. However, Gatwood et al. note the method is used to estimate debris yields for events greater than those with a 5-year recurrence, while post-fire analyses frequently focus on 2-, 5-, and 10-year events.)

Gartner et al. (2014) present two different empirical relationships that differ by the time period of interest; one (the "Emergency assessment model") focuses on the first two years following a fire, and so is most applicable to debris-flow hazards during the emergency mitigation phase, while the other (the "Long-term model") was developed using all available data with no time limit since the most recent fire, and so may be used to estimate the longer-term impact of sediment-laden flows on development in the 2-10 years following a fire. The Emergency assessment model requires a soil burn severity map, and so likely also requires a BARC map; in most cases, other model inputs will be relatively simple to acquire.

Gatwood et al. (2000) can also be used to estimate post-fire sediment/debris, where the effect of the time since the last fire is represented in the Fire Factor, as described in Section 3.2.

Notably, the Gartner et al. (2014) and Gatwood et al. (2000) computations can be performed directly in the U.S. Army Corps of Engineers' HEC-HMS (Hydrologic Modeling System) software (Bartles et al., 2022).

5.2.3.3 POST-FIRE BULKING FACTORS

There is substantial uncertainty in post-fire hydrology models, sediment yield models, and the simple method (Equation 3.1) used by many agencies to distribute sediment throughout a storm hydrograph, particularly in the initial period immediately following a fire. Therefore, we recommend that, whenever possible, bulking factors assigned during the first 2 years following a fire be determined by expert geologists or engineers based on a study of available historical event data and field and geomorphic evidence. Generally, these studies will identify the likely flow type (normal, hyperconcentrated, debris flow), associated rheology, and sediment concentration, which can then be used to compute an associated bulking factor. This method may be more reliable than the available models for these extreme circumstances (Don Lindsay, personal communication, May 3, 2022).[7] In the absence of sufficient data to develop a reasonable bulking factor, we recommend the use of a bulking factor of 2, which corresponds to a debris flow condition and is conservative in all but the most extreme cases.

For planning design in a burned area 2-10 years following a fire, when runoff and debris flow hazards have decreased substantially, we recommend that bulking factors be determined using the same methods described in Section 5.1.3.2, but with an upper limit of 1.7 instead of 1.5. (That is, bulking factors determined using Approach #1 should be constrained to values of 1.2 to 1.7, and the standard conservative value for Approach #2 should be 1.7.) This value corresponds to a sediment concentration of 40 percent, which is approximately the threshold between hyperconcentrated and debris flows and reflects the greatly diminished risk of debris flows 2+ years after a fire.

---

[7] Note that some available hydraulic models are limited in their ability to adequately simulate non-Newtonian flows, and so the results of this classification may affect the subsequent methods used for the hydraulic design of flood conveyance facilities.

6 CONCLUSION

This study was commissioned as part of a current effort to update the 2003 San Diego County Hydrology Manual. Specifically, it addresses questions about whether, how, and where to estimate sediment/debris yields and apply sediment/debris bulking factors in San Diego County, under both normal and post-fire emergency conditions, and how to make emergency estimates of post-fire increases in clear-water runoff. Based on a review of the sediment yield/bulking and post-fire hydrology methodologies used by other public agencies in Southern California, regional differences in watershed conditions, and current best practices, this report makes recommendations about appropriate methodologies for the County of San Diego.

Historically, regional sediment/debris hazard mitigation has mainly been reactive: methods and infrastructure have generally been developed for areas with history of damaging debris and sediment-laden flows. This appears to be changing, as researchers and public agencies recognize the likely future impacts of increasingly frequent and intense fires and increasingly intense rainfall and revisit policies aimed at protecting lives and safety, property, and infrastructure. The past decade has seen substantial growth in the body of literature on post-fire hydrology and sediment/debris hazards, and several Southern California counties are currently undertaking or planning reviews of their current guidance and considering updates.

Given the nonstationary climate and related effects, the limited local sediment/debris yield data available for San Diego County, and the pace of new research, we present this report as a starting point. New advances in remote sensing, such as the use of pre-and post-fire LiDAR-based elevation data to monitor and quantify watershed volume changes, hold great promise for expanding our understanding of sediment production and movement throughout the landscape, especially in data-scarce areas. Due to the expected changes in both hazards and best practices, we envision that any policies established based on the recommendations in this report will be periodically revisited and updated.

7 ACKNOWLEDGMENTS

River Focus, Inc. performed this study for the County of San Diego as a subconsultant to RICK Engineering Company. Mehdi Khalili, PE, MS, CFM, QSD, served as the County of San Diego lead for the study. Laura Henry, PE, and Jayne Janda-Timba, PE, of RICK Engineering Company provided project coordination and guidance.

The authors would also like to thank the following professionals for their valuable assistance and data during this study:

- Martin Araiza, Senior Civil Engineer, Los Angeles County Public Works
- Rex Baum, Supervisory Research Geologist, USGS Landslide Hazards
- Drew Coe, Forester III, Watershed Protection Program Manager, CAL FIRE, Watershed Emergency Response Team
- Wesley Danskin, Research Hydrologist, USGS California Water Science Center
- Suzie Earp, Interim Director, Collections Manager, and Water Historian, California State University Water Resources Institute
- Michael B. Fam, MPA, PE, Engineering Manager/Division Chief, San Bernardino County Flood Control Planning/Water Resources Division, Department of Public Works
- Kyle Gallup, PE, CFM, Engineering Project Manager, Riverside County Flood Control and Water Conservation District
- Ibram Gayed, PE, Supervising Engineer, San Bernardino County Flood Control Planning/Water Resources Division, Department of Public Works
- Jason Kean, Research Hydrologist, USGS Landslide Hazards Program
- Penny Lew, PE, CFM, Sr. Civil Engineer, Orange County Public Works Flood Programs, Floodplain Management & Hydrology Section
- Don Lindsay, CEG, GE, Sr. Engineering Geologist / Geotechnical Engineer, Forest and Watershed Geology Program, California Geological Survey
- Matt Schmid, PE, CFM, Sr. Civil Engineer, County of San Diego Flood Control Engineering
- Yunsheng Su, Ph.D., PE, M. ASCE, D. WRE, CFM, Engineer IV, Ventura County Public Works, Advanced Planning Section, Watershed Protection – Planning & Permits
- Jo Ann Weber, Water Resources Manager, County of San Diego Watershed Protection Program

The bulking factor study report was prepared by Jon Viducich, PE, Senior Hydraulic Engineer, Jake Gusman, PE, Project Manager, Darren Bertrand, CFM, Senior Hydrologist, and Grant Brady, EIT, Hydraulic Engineer.

8 REFERENCES

Alluvial Fan Task Force. (2010). *Findings and recommendations report [draft].* April 2010.

Bacon, S.N., Miller, J.J., & French, R.H. (2013). *Borrego Springs alluvial fan active and inactive area mapping, County of San Diego, California*. Desert Research Institute.

Bartles, M., Brauer, T., Ho, D., Fleming, M., Karlovits, G., Pak, J., Van, N., & Willis, J. (2022). Hydrologic Modeling System HEC-HMS User's Manual. Tech Rep. USACE. Retrieved from https://www.hec.usace.army.mil/confluence/hmsdocs/hmsum/latest

Bedrossian, T. L., Roffers, P., Hayhurst, C. A., Lancaster, J. T., Short, W. R., McCrea, S., Wanish, B., Thompson, J., Carney, A., Myers, M. A., & Utley, S. (2012). *Geologic compilation of Quaternary surficial deposits in Southern California*. California Geological Survey Special Report 217. Retrieved from https://www.conservation.ca.gov/cgs/publications/sr217

Bradley, J.B. (1986). *Hydraulics and bed material transport at high fine suspended sediment concentrations.* (dissertation). Colorado State University, Fort Collins, Colorado.

Cal-Adapt. (2021). Climate Tools. Retrieved from June 1, 2022, from https://cal-adapt.org/tools/

CAL FIRE. (2022). Fire Hazard Severity Zones Maps. Office of the State Fire Marshall. Retrieved from https://osfm.fire.ca.gov/divisions/community-wildfire-preparedness-and-mitigation/wildland-hazards-building-codes/fire-hazard-severity-zones-maps/

California Geological Survey. (2018). *Geology of California.* Scale 1 : 2,000,000. Map Sheet 57. Retrieved from https://www.conservation.ca.gov/cgs/Documents/Publications/Map-Sheets/MS_057-2018-Geology-of-California.pdf

Caltrans. (2020). *Highway design manual*. Seventh edition. Chapter 810: Hydrology. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0810-a11y.pdf

Cannon, S. H., Gartner, J. E., Rupert, M. G., & Michael, J. A. (2004). *Emergency assessment of debris-flow hazards from basins burned by the Cedar and Paradise Fires of 2003, Southern California*. US Geological Survey Open-File Report, p. 1011.

Conedera, M., Peter, L., Marxer, P., Forster, F., Rickenmann, D., & Re, L. (2003). Consequences of Forest Fires on the Hydrogeological Response of Mountain Catchments: A Case Study of the Riale Buffaga, Ticino, Switzerland. *Earth Surface Processes and Landforms*, 28(2), 117-129. DOI: 10.1002/esp.425

County of San Diego. (2014). *San Diego County hydraulic design manual.* County of San Diego Department of Public Works Flood Control Section.

County of San Diego. (2020). *County of San Diego BMP design manual: For permanent site design, stormwater treatment and hydromodification management*. Retrieved from https://www.sandiegocounty.gov/content/dam/sdc/dpw/WATERSHED_PROTECTION_PROGRAM/watershedpdf/Dev_Sup/BMPDM_Complete_Sep2020.pdf

DeBano, L. F. (1981). *Water repellent soils: A-state-of-the-art*. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-46. 21 pp. Retrieved from https://www.fs.fed.us/psw/publications/documents/psw_gtr046/psw_gtr046.pdf

Dibblee, T. W. Jr. (1982). *Regional geology of the Transverse Ranges Province of Southern California.* In Fife, D., (ed). Geology and mineral wealth of the California Transverse ranges: Santa Ana, California: Santa Ana, South Coast Geological Society, Inc., pp. 7–26.

Elliott, J. G., Smith, M. E., Friedel, M. J., Stevens, M. R., Bossong, C. R., Litke, D. W., Parker, R. S., Costello, C., Wagner, J., Char, S. J., Bauer, M. A., & Wilds, S. R. (2005). *Analysis and mapping of post-fire hydrologic hazards for the 2002 Hayman, Coal Seam, and Missionary Ridge wildfires, Colorado*. USGS Scientific Investigations Report 2004-5300, p. 104.

Foltz, R. B., Robichaud, P. R., & Rhee, H. H. (2009). *A synthesis of post-fire road treatments for BAER teams: methods, treatment effectiveness, and decision making tools for rehabilitation.* General Technical Report RMRS-GTR-228. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Retrieved from https://www.fs.usda.gov/treesearch/pubs/32967

Gartner, J. E., Cannon, S. H., & Santi, P. M. (2014). Empirical Models for Predicting Volumes of Sediment Deposited by Debris Flows and Sediment-Laden Floods in the Transverse Ranges of Southern California. *Engineering Geology,* 176:45-56. DOI: 10.1016/j.enggeo.2014.04.008

Gatwood, E., Pederson, J., & Casey, K. (2000). *Los Angeles District method for prediction of debris yield*. U.S. Army Corps of Engineers, Los Angeles District. p. 145.

Guirguis, K., Gershunov, A., Hatchett, B., Shulgina, T., DeFlorio, M. J., Subramanian, A. C., Guzman-Morales, J., Aguilera, R., Clemesha, R., Corringham, T. W., Delle Monache, L., Reynolds, D., Tardy, A., Small, I., Ralph, F. M. (2022). Winter wet–dry weather patterns driving atmospheric rivers and Santa Ana winds provide evidence for increasing wildfire hazard in California. *Climate Dynamics*, p. 1-21, DOI: 10.1007/s00382-022-06361-7

Gusman, A. J., Teal, M. J., Todesco, D., & Bandurraga, M. (2011). *Sediment/debris bulking factors and post-fire hydrology for Ventura County*. WEST Consultants Inc., San Diego, California.

Inman, D. L., & Jenkins, S. A. (1999). Climate Change and the Episodicity of Sediment Flux of Small California Rivers. *The Journal of Geology*, v. 107, p. 251–270, DOI: 10.1086/314346.

Jones, E. S., Mirus, B. B, Schmitt, R. G., Baum, R. L., Burns, W. J., Crawford, M., Godt, J. W., Kirschbaum, D. B., Lancaster, J. T., Lindsey, K. O., McCoy, K. E., Slaughter, S., & Stanley, T. A. (2019). *Summary metadata – Landslide inventories across the United States*. U.S. Geological Survey data release, DOI: 10.5066/P9E2A37P

Kean, J. W., Staley, D. M., & Cannon, S. H. (2011). In Situ Measurements of Post-Fire Debris Flows in Southern California: Comparisons of the Timing and Magnitude of 24 Debris-Flow Events with Rainfall and Soil Moisture Conditions. *Journal of Geophysical Research*, 116, F04019. DOI: 10.1029/2011JF002005

Kean, J. W., & Staley, D. M. (2021a). Forecasting the Frequency and Magnitude of Postfire Debris Flows Across Southern California. *Earth's Future*, 9(3), e2020EF001735. DOI: 10.1029/2020EF001735

Kean, J. W., & Staley, D. M. (2021b). *Gridded estimates of postfire debris flow probability and magnitude for southern California*. U.S. Geological Survey data release. DOI: 10.5066/P91GIT04

Kinoshita, A., Hogue, T. S., & Napper, C. (2013). *A guide for pre- and post-fire modeling and application in the western United States*. USDA Forest Service, National Technology and Development Program, 1325 1802—SDTDC. Retrieved from https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcseprd1805302&ext=pdf

Lamb, M. P., J.S. Scheingross, J. S., W.H. Amidon, W. H., Swanson, E., & Limaye, A. (2011). A Model for Fire-Induced Sediment Yield by Dry Ravel in Steep Landscapes. *Journal of Geophysical Research*. Vol. 116, F03006, DOI: 10.1029/2010JF001878

Los Angeles County. (2006a). *Hydrology Manual*. Department of Public Works, Water Resources Division. Retrieved from https://dpw.lacounty.gov/wrd/publication/engineering/2006_Hydrology_Manual/2006%20Hydrology%20Manual-Divided.pdf

Los Angeles County. (2006b). *Sedimentation Manual, 2nd edition*. Department of Public Works, Water Resources Division. Retrieved from https://dpw.lacounty.gov/wrd/publication/engineering/2006_sedimentation_manual/Sedimentation%20Manual-Second%20Edition.pdf

Moody, J. A. (2012). *An analytical method for predicting postwildfire peak discharges.* U.S. Geological Survey Scientific Investigations Report 2011–5236, p. 36

Mussetter Engineering Inc. (2008). Sediment and Erosion Design Guide. *Prepared for Southern Sandoval County Arroyo Flood Control Authority*. Retrieved from https://sscafca.org/development/documents/sediment_design_guide/Sediment%20Design%20Guide%2012-30-08.pdf

Neely, A. B., DiBiase, R. A., Corbett, L. B., Bierman, P. R., & Caffee, M. W. (2019). Bedrock Fracture Density Controls Hillslope Erodibility in Steep, Rocky Landscapes with Patchy Soil Cover, Southern California, USA. *Earth and Planetary Science Letters*, 522, pp. 186-197. DOI: 10.1016/j.epsl.2019.06.011

O'Brien, J. S. (2006). *FLO-2D user's manual.* Version 2006.01, January 2006. Nutrioso, AZ: FLO-2D Software, Inc.

O'Brien, J. S., & Fullerton, W. T. (1989). *Hydraulic and sediment transport study of Crown Pointe flood wall: Breckenridge, CO.* Lenzotti and Fullerton Consulting Engineers, Inc., p. 34.

Riverside County. (1978). *Hydrology manual.* Riverside County Flood Control and Water Conservation District. https://rcflood.org/Portals/0/Downloads/Hydrology-Manual-20180814.pdf?ver=2020-02-05-091623-987

Robichaud, P. R., Elliot, W. J., & Wagenbrenner, J. W. (2011). *Probabilistic soil erosion modeling using the erosion risk management tool (ERMIT) after wildfires*. ISELE Paper Number 11039. Paper presented at the international symposium on erosion and landscape evolution; September 18-21, 2011; Anchorage, AK. Retrieved from https://www.fs.usda.gov/treesearch/pubs/41494

Rowe, P. B., Countryman, C. M., & Storey, H. C. (1949). *Probable peak discharges and erosion rates from Southern California watersheds as influenced by fire*. USDA, Forest Service, California, Forest and Range Experimental Station.

Rowe, P. B., Countryman, C. M., & Storey, H.C. (1954). *Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in Southern California watersheds*. USDA, Forest Service, California Forest and Range Experimental Station.

Santi, P., Higgins, J., Cannon, S., & DeGraff, J. (2006*). Evaluation of post-wildfire debris flow mitigation methods and development of decision support tools*. Report to USGS and the Joint Fire Science Program, 78 p.

Santi, P., & Morandi, L. (2012). Comparison of Debris-Flow Volumes from Burned and Unburned Areas. *Landslides*, 9, 1-13. DOI: 10.1007/s10346-012-0354-4

Scott, K. M., & Williams, R. P. (1978). Erosion and Sediment Yields in the Transverse Ranges, Southern California. *USGS Prof. Paper,* 1030, Washington, D.C. DOI: 10.3133/pp1030

Silver Jackets. (2020). *Flood after fire: California toolkit*. Version 1. Retrieved from https://silverjackets.nfrmp.us/State-Teams/California/Flood-After-Fire-California-Toolkit

Staley, D. M., Negri, J. A., Kean, J. W., Tillery, A. C., & Youberg, A. M. (2016). *Updated logistic regression equations for the calculation of post-fire debris-flow likelihood in the western United States*. U.S. Geological Survey Open-File Report 2016-1106. Retrieved from http://pubs.usgs.gov/of/2016/1106

Staley, D. M., Negri, J. A., Kean, J. W., Laber, J. L., Tillery, A. C., & Youberg, A. M. (2017). Prediction of Spatially Explicit Rainfall Intensity-Duration Thresholds for Post-Fire Debris-Flow Generation in the Western United States. *Geomorphology*, 278, 149– 162. DOI: 10.1016/j.geomorph.2016.10.019

State of California Department of Water Resources. (1977). *Erosion and sedimentation in San Diego County (Calif.) watersheds*. District Report.

Stoof, C. R., Vervoort, R. W., Iwema, J., Van Den Elsen, E., Ferreira, A. J. D., & Ritsema, C. J. (2012). Hydrological Response of a Small Catchment Burned by Experimental Fire. *Hydrol. Earth Syst. Sci.*, 16, 267–285, DOI: 10.5194/hess-16-267-2012

Tatum, F. E. (1963). *A new method of estimating debris storage requirements for debris basins, U.S*. Army Engineer District, Los Angeles, California, Rept., p. 23.

U.S. Department of Agriculture. (2016). *Hydrologic analyses of post-wildfire conditions*. Hydrology Technical Note No. 4. Retrieved from https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=39877.wba

U.S. Forest Service. (n.d.). *Burned area emergency response - BAER*. Retrieved May 19, 2022 from https://www.fs.fed.us/naturalresources/watershed/burnedareas-background.shtml

U.S. Geological Survey. (2009). *Debris flow in action*. Photo taken September 15, 2009. Retrieved May, 27 2022, from https://www.usgs.gov/media/images/debris-flow-action

Vanoni, V. A., (Ed). (2006). *Sedimentation engineering.* Manuals and Reports on Engineering Practice No. 54. American Society of Civil Engineers: Reston, VA.

Ventura County. (2017). *Design hydrology manual*. Ventura County Watershed Protection District. Retrieved from https://www.vcpublicworks.org/wp/hydrologymanual/

Warrick, J. A., & Mertes, L. A. K. (2009). Sediment Yield from the Tectonically Active Semiarid Western Transverse Ranges of California. Geological Society of America Bulletin. 121 (7/8), 1054–1070. DOI: 10.1130/B26452.1

Wells, W.G. II. (1981). Some Effects of Brush Fires on Erosional Processes in Coastal Southern California. In: Davies, T.R.H., Pearce, A.J. (Eds.). Proceedings of the symposium on erosion and sediment transport in Pacific Rim steeplands; 1981 January 25-31; Christchurch, New Zealand. Washington, DC: *International Association of Hydrological Sciences*, Vol 132, 305-342

Wilder, B., Lancaster, J., Cafferata, P., Coe, D., Swanson, B., Lindsay, D., Short, W., & Kinoshita, A. M. (2020). An Analytical Solution for Rapidly Predicting Post-Fire Peak Streamflow for Small Watersheds in Southern California. *Hydrological Processes*. 35, 1–14. DOI: 10.1002/hyp.13976

Wohlgemuth, P. M., & Lilley, K. A. (2018). Sediment delivery, flood control, and physical ecosystem services in southern California chaparral landscapes. Valuing Chapparal. Springer Series on Environmental Management. Springer, Cham. pp. 181-205. DOI: 10.1007/978-3-319-68303-4_7

APPENDIX A

“Technical Memorandum (Draft)” dated December 7, 2020
San Diego County Hydrology Manual
TAC Subcommittee Recommendations

Technical Memorandum (Draft)

Date:	Monday, December 07, 2020
Project:	San Diego County Hydrology Manual TAC Subcommittee
To:	San Diego County Hydrology Manual TAC
From:	Mark Seits
Subject:	San Diego County Hydrology Manual TAC Subcommittee Recommendations

Four subcommittees were formed in support of the San Diego County Hydrology Manual Technical Advisory Committee (TAC). The purpose of the subcommittees was to address outstanding TAC comments from the ongoing review of the current Hydrology Manual procedures in four specific areas:

- C-Values
- Time-of-Concentration
- Bulking Factors
- Calibration

The specific comments raised are included in the Appendix.

Subcommittees were formed from existing TAC members who expressed a specific interest in one or more of the topics. Up to three meetings were held over a period of several months. The following 5-step approach was used to address the issues and make recommendations:

- Understand the problem (issues to be based on TAC comments)
- Understand everyone’s interests
- List possible solutions
- Evaluate options
- Make recommendations

Based on the results of the meetings, the following recommendations were identified for each of the topics. Note: General consensus was reached on each of the recommendations unless otherwise specified.

C-Value Subcommittee

Subcommittee Members: Luis Parra, Tory Walker, Laura Henry, Melisa Wiedemeier, Robert Reiner, Charles Mohrlock, Matt Moore, Vicky Zhang, Joshua Bayona, Tina Fransson, Cassie Sparks

Meeting Dates: August 19, 2020, September 16, 2020, October 21, 2020

Problems/Issues to be addressed:

- Current constant loss rate does not reflect actual watershed conditions during a storm event (loss rate decreases with increased intensity);
- Constant versus variable loss function to be considered;
- Impacts to existing studies/projects based on revised methodology;
- Calibration impacts on potential revisions and vice versa;
- Impacts to existing models/software;
- Simplicity (i.e. ability to do hand calculations);
- Water quality applications (volume versus peak flow based BMPs);

Potential Solutions:

- Constant loss rates (similar to current SD County);
- Simple curve (similar to OCPW);
- Multiple curves (similar to RCFC&WCD and SBCFCD);
- Specified values (mapped values similar to LACFCD);

Recommendations:

- Adopt a new procedure in which C varies based on intensity. Procedure would be similar to that used in OCPW, SBCFCD and RCFC&WCD. The procedure developed for the San Diego manual would link the Rational Method extended to an entire hydrograph and the NRCS Method so that the runoff volume of both methods is identical for the 24 hour storm event.
- The runoff coefficient C should be a function of the rainfall intensity (I, in/hr), the fraction of the area that is impervious (a_i), the overall infiltration for the pervious portion (F_P) and the assigned value of precipitation that becomes runoff under 100% impervious conditions (C_{IMP}). The following is the recommended formula for its determination [1]:

  $$C = C_{IMP} - (1-a_i)\cdot F_P/I \qquad \text{if } I\cdot C_{IMP} > F_P$$
  $$C = C_{IMP}\cdot a_i \qquad \text{if } I\cdot C_{IMP} \le F_P$$

- An average value of $C_{IMP} = 0.93$ is recommended as a simplification to use in the C equation because it represents the expected percentage of rainfall that becomes runoff over impervious surfaces when a 100 yr – 24 hour storm event occurs with a magnitude similar than that expected in most areas of San Diego County. Other values of CIMP in the range (0.9, 0.95) can be used if properly justified by the designer, and approved by the reviewing agency [1].
- FP (in/hr) should be assigned as the constant infiltration loss needed to generate a percentage of runoff identical to the fraction of Precipitation P that becomes runoff Q_a according to Equation 4-4 of the Manual, for a given average CN value assigned to the studied area. A process for this is presented in C Coefficient for Peak Flow and Hydrograph Calculations; Luis Parra, Ph.D., P.E., D.WRE, CFM; no date.
- Since the process to determine F_P could be cumbersome and time consuming; a direct graphical determination and/or equation should be developed.
- Since the proposed methodology for determination of C is based on a 24-hour storm event, and since the Intensity-Duration curve is no longer limited to 6-hours, it is

recommended that reference to the 6-hour storm for detention (Section 6 of the Hydrology Manual, Rational Method Hydrograph) be replaced with the 24-hour storm. This means the standard for detention basin design would be the 24-hour storm event.

What we need in order to implement the recommendations for C-value:

- Obtain agreement from TAC to adopt the new method for C *AND* adopt 24-hour storm event as the standard for detention basin design *AND* adopt new time of concentration procedure as the proposed procedure for C is not compatible with the current procedure for T_c (it results in a loop calculation that continues until T_c is less than 5 minutes).
- Hire consultant to prepare direct graphical determination and/or equation for F_P.
- Hire consultant to update text of hydrology manual and workbook calculations with new procedure for C, as appropriate.

References:

1. C Coefficient for Peak Flow and Hydrograph Calculations; Luis Parra, Ph.D., P.E., D.WRE, CFM; no date;
2. Evaluation of Rational Method “C” Values; Joe Hill, June 2002;
3. Study of Rational Method Runoff Coefficients for Update to June 2003 San Diego County Hydrology Manual; Rick Engineering Company, August 22, 2013;

Time-of-Concentration

Subcommittee Members: Luis Parra, Tory Walker, Eric Mosolgo, Kiran Pallachulla, Laura Henry, Melisa Wiedemeier, Scott Cartwright, Charles Mohrlock, Robert Torres, Vicky Zhang, Joshua Bayona

Meeting Dates: August 26, 2020, September 24, 2020, October 29, 2020

Problems/Issues to be addressed:

- Main concern is with the initial overland flow (T_i) approach;
- Current methodology is too convoluted; needs to be simple, user-friendly, consistent/replicable;
- Need to define limitations on use of T_i (i.e. maximum length, maximum time, maximum area, etc.);
- Impact of potential changes to the C-value approach needs to be considered if C-value is an input parameter to the T_i (i.e. potential iterative process if both C and T_i are functions of intensity);
- Need to consider approach to computed T_c for downstream concentration points if T_i is less than 5 minutes;
- Approach for junctions could also be considered;

Potential Solutions:

- Existing approach with additional clarification/definition on use;
- Single nomograph (similar to OCPW, RCFC&WCD, SBCFCD) with defined limits/application;
- Search recent literature (i.e. last 20 years) for newer approach/trend;

Recommendations:

Recommendations for the time of concentration (T_c):

- Adopt T_i nomograph (and equation form) similar to OCPW, SBCFCD and RCFC&WCD.
- Encourage use of the T_i equation form by providing equation and K values (K values represent ground cover, and fraction of impervious area).
- Limit use of T_i nomograph to 330 feet (100 m) for urban areas and 660 feet (200 m) for undeveloped areas is recommended; this is consistent with OCPW limits and is partially based on HEC 22.
- Add language regarding application and use of T_i nomograph (e.g. flow must be predominantly sheet flow, but some shallow confinement is okay; also need to understand impact on downstream flow calculations if T_c is too high or too short).
- It was confirmed that a computed T_i less than 5-minutes should be used for the next downstream routing;
- Adopt a modified junction equation for when the smaller T_c results in the larger confluence Q; a ratio of I_1/I_2 (greater than 1) should be included with the T_1/T_2 (less than 1) to adjust the larger stream Q to account for both the reduced area (T_1/T_2) as well as the higher average intensity for the shorter T_c; net result will still be less than 1, but higher than current equation (uses T_1/T_2 only); The ratio of I-Fm (as opposed to just I) could also be considered as peak flow is physically proportional to effective intensity I-Fm and this more accurate expression is used in SBCFCD and OCPW manuals

What we need in order to implement the recommendations for initial time of concentration and junction equation:

- Obtain agreement from TAC to adopt new initial time of concentration procedure.
- Hire consultant to prepare equation and K values for T_i, as appropriate. The equation can be obtained from AES software, as it has been included in the software modules for other agencies. K values can be obtained from AES software. However, additional K values are desired to represent different ground cover quality (poor, fair, good) in the pervious fraction of the subarea.
- Obtain agreement from TAC to adopt new junction equation.
- Hire consultant to update text of hydrology manual and workbook calculations with new procedure for time of concentration and new junction equation, as appropriate.

References:

1. Department of Transportation Federal Aviation Administration Advisor Circular No. 150/5320-5B; July 1, 1970;

2. Initial Time of Concentration Analysis of Parameters; Joe Hill, June 2002;
3. Tc Comparison Calculations for Various Methods; AECOM, December 2, 2014;

Bulking Factor

Subcommittee Members: Matt Schmid, David Smith, Jake Gusman, Dragi Stefanovic

Meeting Dates: September 2, 2020, October 8, 2020, November 4, 2020

Problems/Issues to be addressed:

- Need to better define Sediment Yield methods (including upper and lower bounds, event versus average annual yield)
- Need to address Sediment and Debris Bulking Factor
- Need to address Post-Fire Hydrology/Debris
- Need for Sediment Transport (include here or Hydraulic Design Manual)
- Need for Erosion Control (include here or BMP/Stormwater Manual)
- How to address Alluvial Fans
- How much to include in the manual or just reference to other manuals
- Identify areas in the County susceptible to landslides
- Identify areas in the County susceptible to wildfires

Potential Solutions:

- Include Introduction Section that describes purpose/use of SY (debris basins, reservoirs, bulking factor for flood control facilities, erosion control facilities, watershed erosion)
- Sediment Yield Methods: RUSLE2/MUSLE, LA County (includes fire flow factor, A-T factor), Dendy/Bolton (500+ reservoirs), Taylor, others?
- Option 1: Identify “default” method (table, curve, etc.) to use as upper limit (or if applicant doesn’t want to do other analyses), but allow for other methods if applicable (applicant would need to compare options and defend recommendation)
- Option 2: Include multiple options and require applicant to compare results and defend recommendation

Recommendations:

Recommendation for the Bulking Factor:

- Recommend use of “Upper Curve/Limit” with the option to compute watershed specific value if it can be defended (subject to 3rd Party Review); Examples could include LA County, Riverside County, Ventura County, etc. (see Figures 6-6, 13-2 and 13-3 from Ventura County Report [1]); it was also recommended to create a map of high risk areas to be considered for BF application; map could be based on chronic problem areas, slope, vegetation, geology, etc.;

Recommendation for Post-fire Hydrology:

- Recommend including a new section with a general overview and application, but not prescriptive methodology; include references of where to find additional information;

Recommendation for Alluvial Fans:

- Recommend not adding separate section, but add a reference to County policy, etc.;

Revisions to the following sections were previously provided to NV5 in response to TAC comments:

- Sediment Yield
- Sediment Transport
- Erosion Control

What we need in order to implement the recommendations for the Bulking Factor, Post-Fire Hydrology and Alluvial Fans:

- Obtain agreement from TAC to adopt use of upper limit for bulking factor.
- Obtain agreement from TAC to develop new section to cover post-fire hydrology overview and application.
- Obtain agreement from TAC to add reference to County policy on Alluvial Fans.
- Hire consultant to update text of hydrology manual and workbook calculations with revised/new sections, as appropriate.

References:

1. Sediment/Debris Bulking Factors and Post-Fire Hydrology for Ventura County, WEST Consultants; June 2011;

Calibration

Subcommittee Members: Tory Walker, Kiran Pallachulla, Hassan Tavakol, Anthony Cotts, Venkat Gummadi, Brendon Hastie, Eric Mosolgo, Melisa Wiedemeier, Anthony Barry, Jake Gusman, Charles Mohrlock, David Smith, Luis Parra

Meeting Dates: October 14, 2020, November 11, 2020

Problems/Issues to be addressed:

- Need to identify a framework for how calibration may be done in the future;
- Need to define goals for calibration (e.g. improve accuracy, comparison to historical events, confidence in design flows, etc.)
- Data availability will be key; need to check NPDES monitoring (e.g. 5-year HMP Study) and other data sources (including outside of SD County); new gages also need to be considered;
- Need to consider both small and large watersheds (i.e. rational method and NRCS applications); most issues have been with smaller watersheds; however, some of

those issues may be addressed with other manual revisions (e.g. NOAA Atlas rainfall, C-values, etc.);

- Need to address large discrepancy between Rational Method and NRCS methods at 1 sq.mi.
- Need to consider potential changes from other subcommittees (e.g. Tc and C-Values), but broad-based changes to these parameters are not intended to be considered as part of the calibration effort (although refinements could be recommended based on the calibration effort);
- PZN adjustments are too complicated and may be simplified or removed/replaced completely (e.g. consideration of AMC in lieu of PZN);
- Need to consider 2013 Rainfall Distribution Study [1] and how it might be used to improve short-term guidance to the HM;
- It was suggested that we submit a request for new gages as soon as possible; consideration should be given for data gaps throughout the County; need to map;
- It was suggested we could reach out to all of the incorporated communities (i.e. co-permittees) and other governmental agencies, including FEMA, for additional data sources, including watershed studies (e.g. Los Coches, Los Penasquitos, Carroll Canyon, San Dieguito, San Diego River, etc.);

Potential Solutions:

- Leverage county-wide data call (rainfall, runoff, watershed studies, etc.);
- Identify/map locations for new gages (rainfall and runoff) and get process started;
- Consider short-term revisions that could be implemented this year and then identify other actions for longer term consideration;

Recommendations:

- Complete a comprehensive Data Collection effort including:
  - List/map of all existing gages (rain and stream) within the County;
  - Watershed studies (where some calibration may have been done);
  - NPDES/WQIP data;
- Identify/Map Data Gaps
- Review/evaluate watershed studies to determine if findings can be used to help identify short-term guidance for use of updated Hydrology Manual;
- Perform a detailed calibration of the existing HEC-HMS models from 2013 Rainfall Distribution study to improve the short-term guidance for the Hydrology Manual.
- Complete a comprehensive Calibration Study to address 2-100 year frequencies; this is intended to be a long-term solution and will depend on availability, quality and applicability of data; the need for this level of calibration was not agreed to by all subcommittee members, but there was general consensus that some level of calibration would be beneficial;
- Consider potential impacts of Climate Change; monitor what state and federal agencies are requiring;

- Incorporate flexibility in modeling approach (Rational Method versus NRCS) near 1 square-mile watershed size;

What we need in order to implement the recommendations for the Calibration:

- Obtain agreement from TAC to perform short-term and/or long-term calibration efforts.
- County staff or hire consultant to complete Data Collection effort and identify Data Gaps.
- Hire consultant to perform calibration on HEC-HMS models from 2013 Rainfall Distribution Study.
- Consider future effort to complete comprehensive calibration for 2-100 year frequencies;
- County staff to monitor state and federal guidelines on consideration of Climate Change.

References:

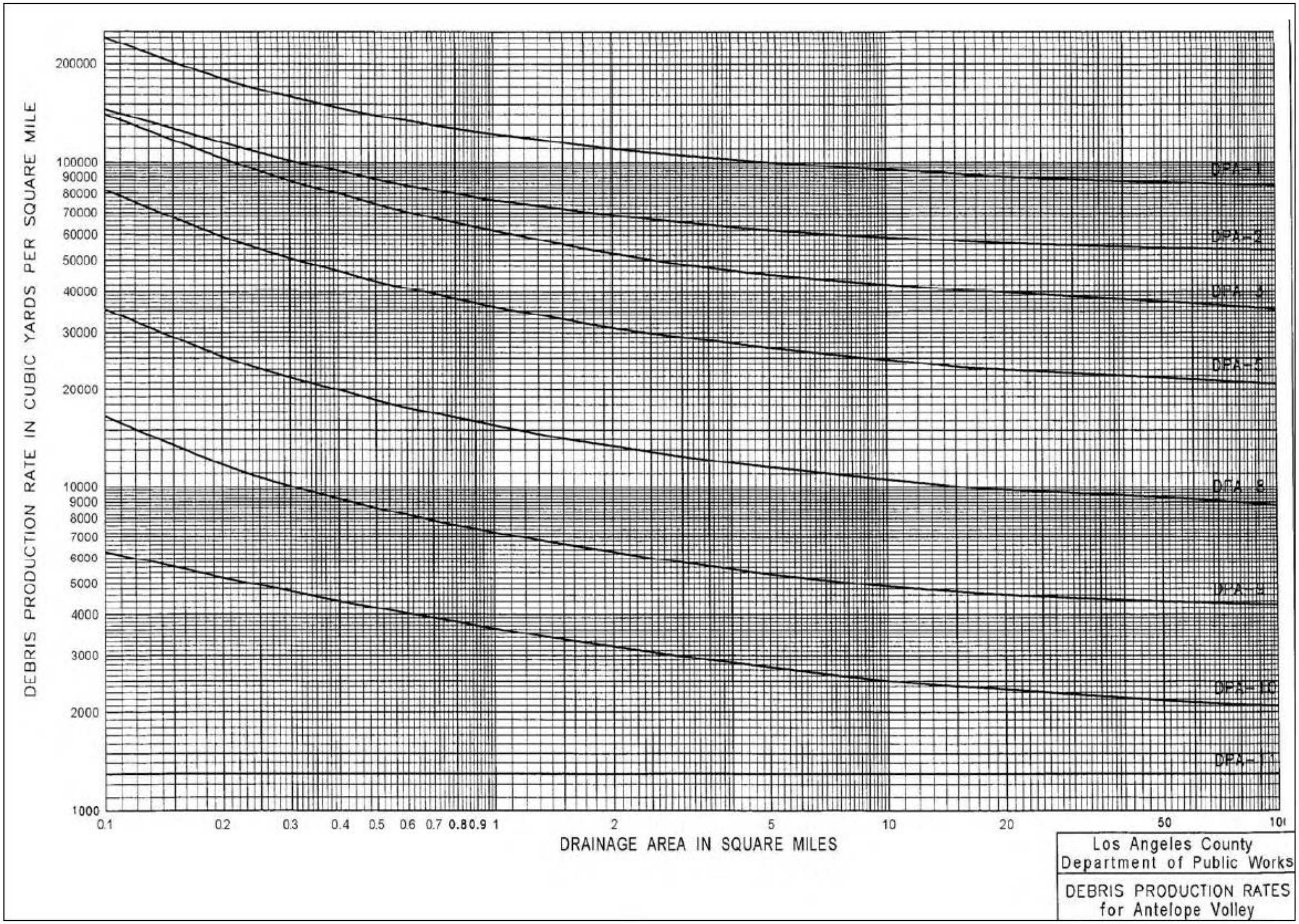
1. Analysis of Results for the County of San Diego Rainfall Distribution Study Project; Bureau Veritas, March 5, 2013;
2. Derivation of a Rainfall-Runoff Model to Compute N-Year Floods for Orange County Watersheds; November 1987
3. Report on the Calibration Analysis for the San Diego County Hydrology Manual; Hromadka & Associates, May 2007;

Next Steps

- Present recommendations to TAC (December) for consideration;
- Confirm potential updates for ongoing versions or defer for future update(s);
- Continue discussions with Staff, TAC and Subcommittees, as needed;

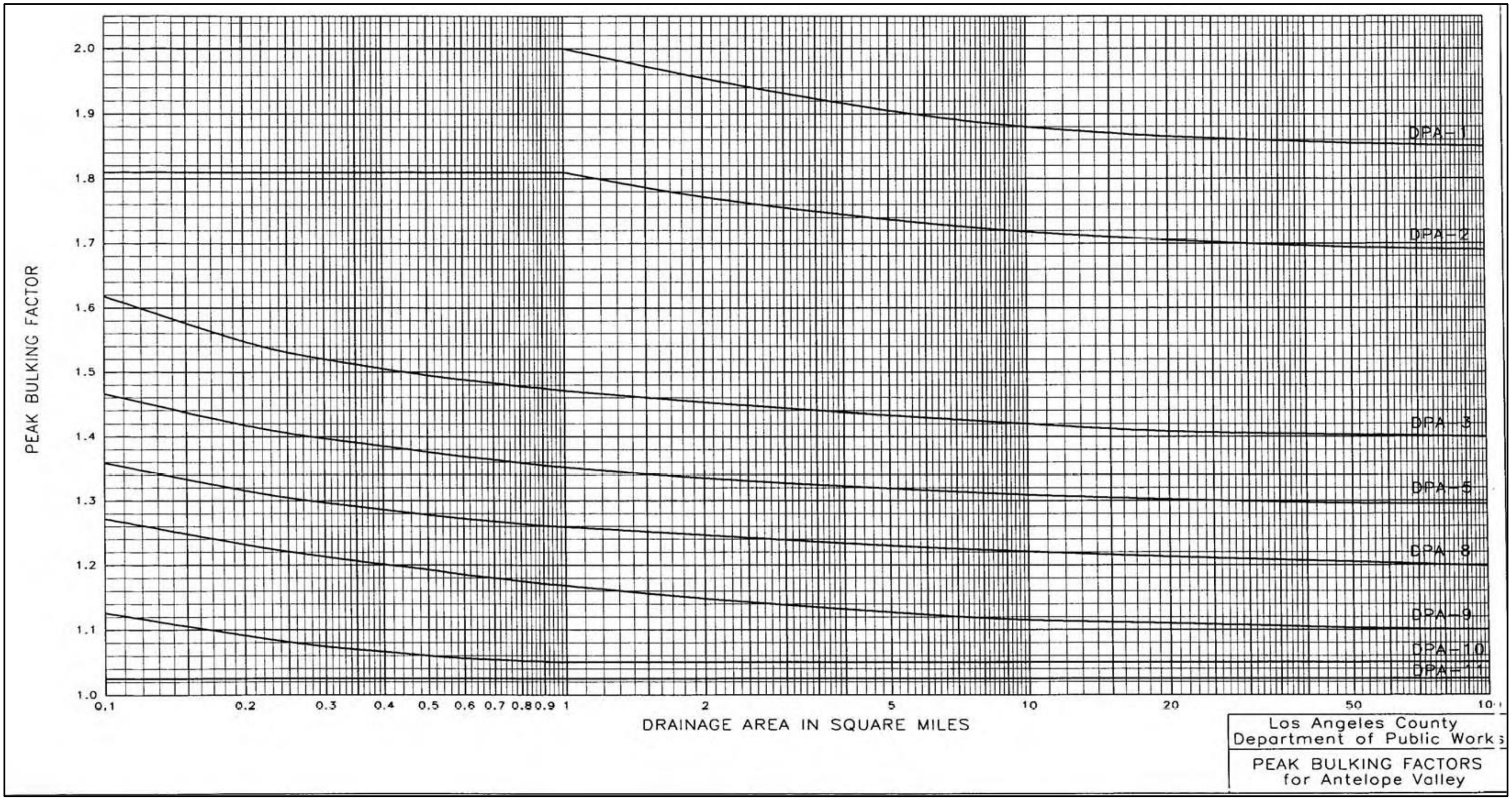
APPENDIX B

Peak Debris Production Ratio and Bulking Factor Curves for Selected Basins in Los Angeles County, Based on Drainage Area (From Appendix B; Los Angeles County, 2006b)



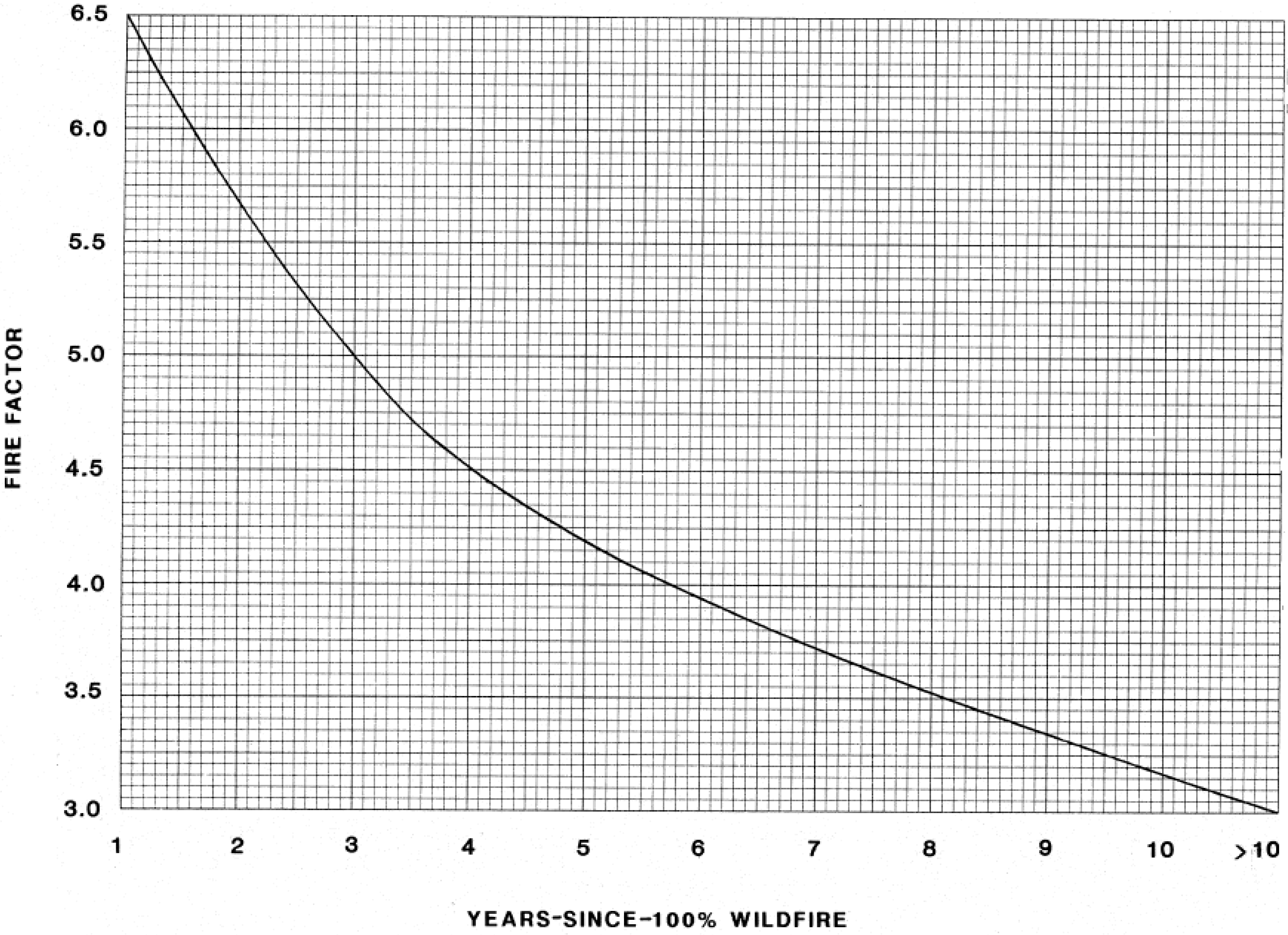
Los Angeles County
Department of Public Works

DEBRIS PRODUCTION RATES
for Antelope Volley


PEAK BULKING FACTOR
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
5
10
20
50
10
DRAINAGE AREA IN SQUARE MILES
DPA-1
DPA-2
DPA-3
DPA-5
DPA-8
DPA-9
DPA-10
DPA-11
Los Angeles County
Department of Public Works
PEAK BULKING FACTORS
for Antelope Valley

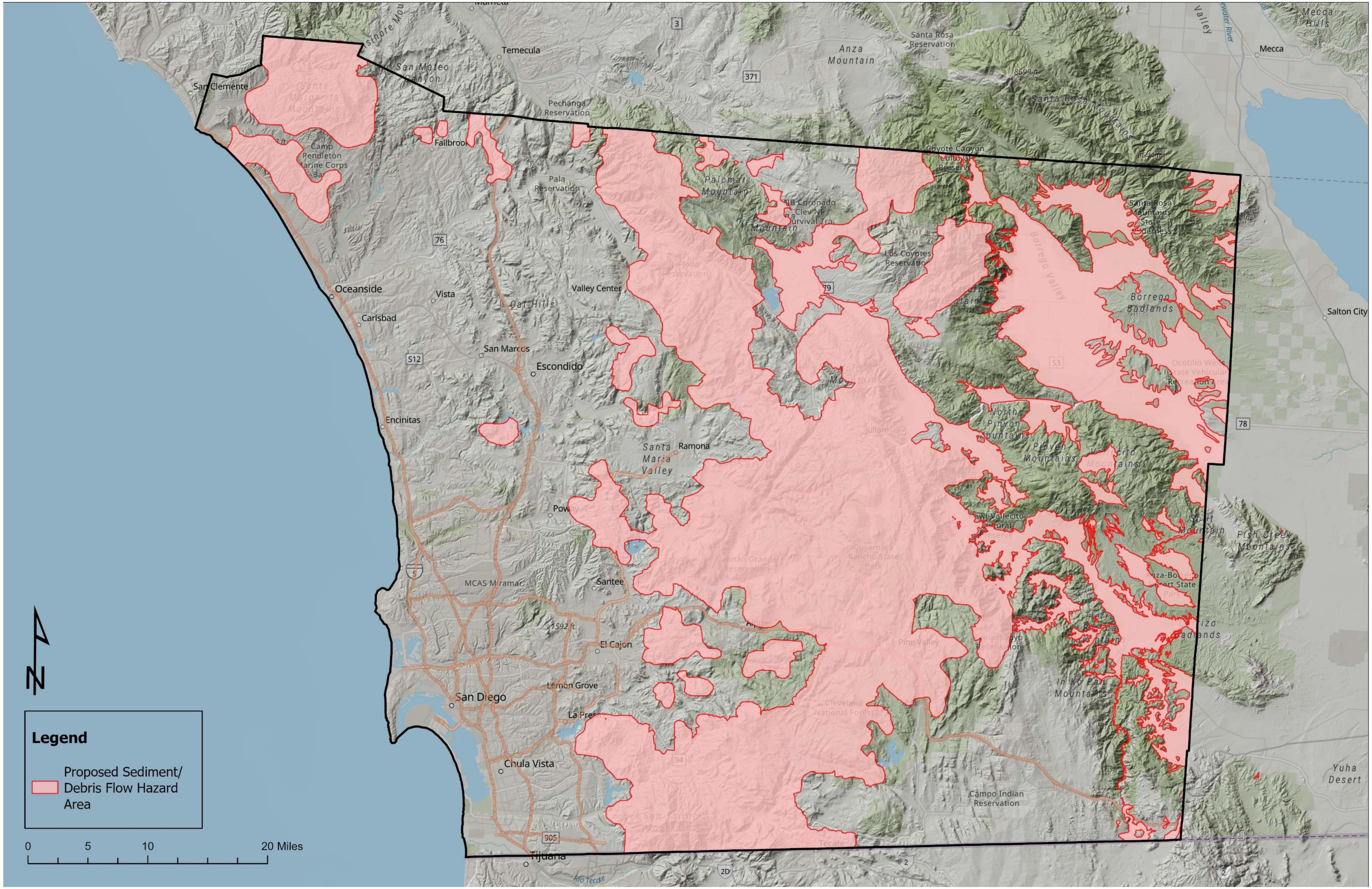
APPENDIX C

Fire Factor (FF) Curve for Watersheds 0.1 to 3.0 mi^2
(Gatwood et al., 2000)


6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
FIRE FACTOR
1
2
3
4
5
6
7
8
9
10
>10
YEARS-SINCE-100% WILDFIRE

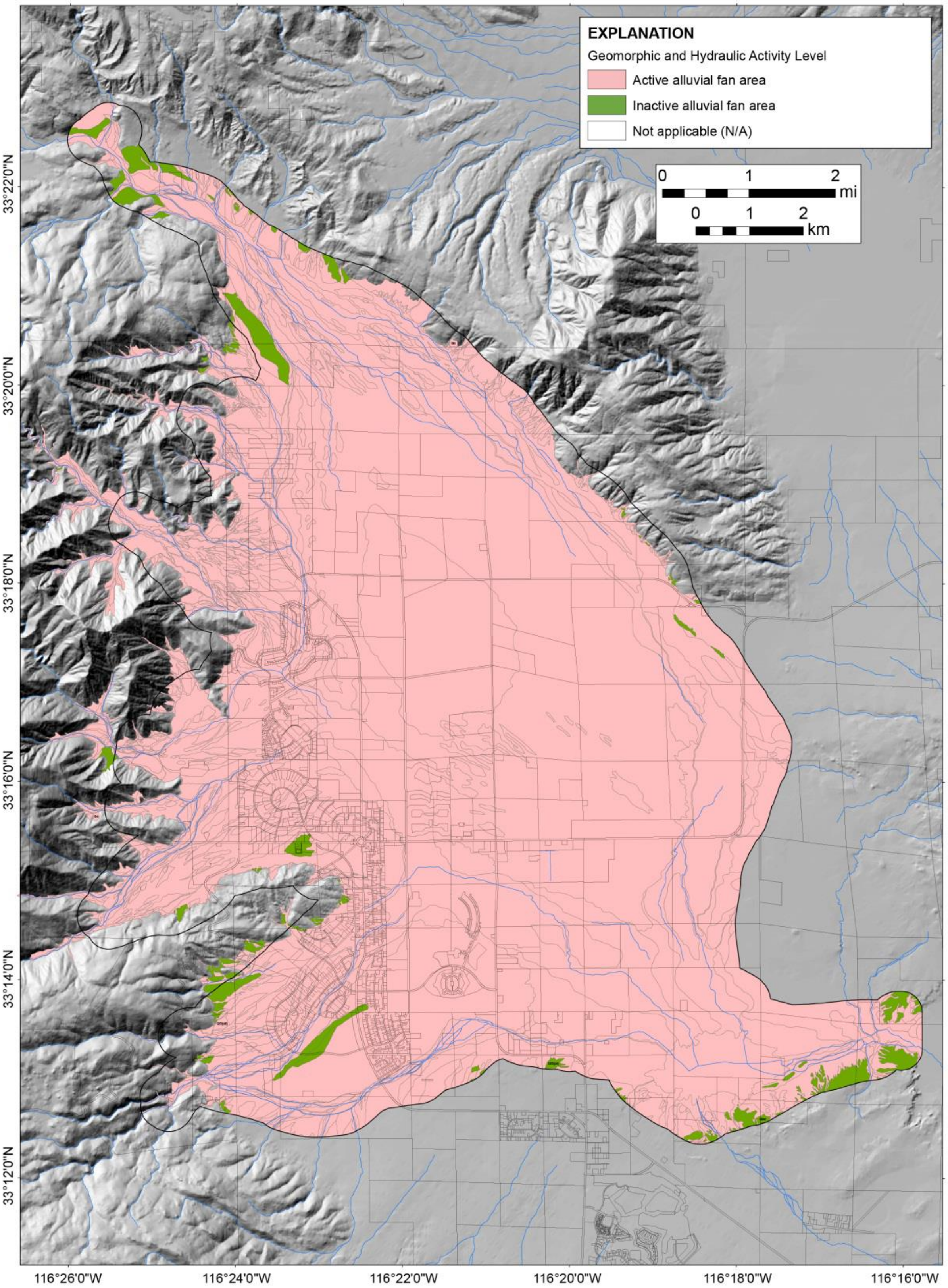
APPENDIX D

High-risk Areas Requiring Case-by-case Sediment Hazard Assessment


Legend
🟥 Proposed Sediment/ Debris Flow Hazard Area
0 5 10 20 Miles
N
Temecula
Anza Mountain
Santa Rosa Reservation
Mecca
San Clemente
Pechanga Reservation
Fallbrook
Camp Pendleton Marine Corps Base
Pala Reservation
Palomar Mountain
Los Coyotes Reservation
Coyote Canyon
Santa Rosa Mountains State Wilderness
Borrego Valley
Borrego Badlands
Salton City
Oceanside
Vista
Carlsbad
Valley Center
San Marcos
Escondido
Encinitas
Ramona
Santa Maria Valley
North Pinyon Mountains
Pinyon Mountains
Poway
MCAS Miramar
Santee
El Cajon
Lemon Grove
San Diego
Chula Vista
Fish Creek Mountains
In Ko Pah Mountains
Campo Indian Reservation
Yuha Desert
Tijuana
Mecca Hills

APPENDIX E

Geomorphic and Hydraulic Alluvial Fan Activity Map of the Borrego Valley (Bacon, Miller, & French, 2013)


EXPLANATION
Geomorphic and Hydraulic Activity Level
Active alluvial fan area
Inactive alluvial fan area
Not applicable (N/A)
0 1 2 mi
0 1 2 km
33°22'0"N
33°20'0"N
33°18'0"N
33°16'0"N
33°14'0"N
33°12'0"N
116°26'0"W
116°24'0"W
116°22'0"W
116°20'0"W
116°18'0"W
116°16'0"W