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16. ABSTRACT

Currently Caltrans is searching for a methodology to determine sediment bulking specific to Northern California, In Southern California, there are specific, existing methods and equations in use by Caltrans. Due to increased wildfire occurrence and severity in northern and southern California, a regionalized sediment bulking method for California watersheds would allow Caltrans to design better hydraulic and stormwater facilities. This prepares Caltrans for climate change and the resulting increase wildfire potential to create a more sustainable roadway design.

The research will benefit Caltrans by having roadways that are more resilient and safer. The methodology can be used by local and state agencies to create safer and more sustainable infrastructure. Also, this research will provide a defensible justification and method for sizing drainage facilities that account for sediment bulked associated with wildfires.

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Regional Sediment Bulking Methods for California in Support of Post Wildfire Flood Mitigation

- Final Report -

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1. Introduction

1.1. Background Information

Post-fire debris flows/floods are extremely dangerous geo-hazards due to their sudden onset, high velocity, and destructive power (Cui et al., 2018), and are a growing threat in California as changing climatic patterns lead to higher risk of high-burn-severity wildfires and intense rains (Silver Jackets, 2020). High soil burn severity can lead to the creation of hydrophobic soils, which increase the risk of landslides and flood hazards as the soil repels water, reducing infiltration and increasing the volume of runoff in a watershed (VanDine et al., 2005). This increased runoff reduces the rainfall threshold needed to trigger debris flows. In addition, burnt material has lower internal friction angle and cohesion, which makes it more easily mobilized (Cui et al., 2018), and loss of vegetation to fire reduces the stabilizing effect of roots and infiltration of water, increasing runoff and debris flow generation potential (Wall et al., 2020). As a result, when intense rains occur on recently burned hillslopes, debris flows and flash floods may occur (Rengers et al., 2016) Risk of erosion and post-fire debris flow decreases as vegetation recovers. Time since the last burn is an important factor affecting risk of post-fire debris flow (Hoch et al., 2021). Sediment yields from burned watersheds are highest within the first two years since the fire, after which they typically decrease by an order of magnitude, though recovery rates differ across regions and ecosystems (Robichaud et al., 2010). These realities make it important that infrastructure is designed to account for potential post-fire flood flows, whether they be normal flow, hyperconcentrated flow, or debris flow.

To account for increasing concentrations of sediment in streamflow, modelers often use bulking methods with which to increase discharge above the expected normal flow by the volume of sediment added to the flow (West Consultants, 2011; Gusman et al., 2009; Highway Design Manual: Chapter 810 - Hydrology, 2020 *Highway Design Manual: Chapter 810 - Hydrology*) Figure 1 shows a flow classification scheme based on sediment concentration and bulking factor adopted from Gusman et al. (2009). Bulking factors have been estimated based on historically observed sediment concentrations, but the data to support these estimations have been limited (Highway Design Manual: Chapter 810 - Hydrology, 2020). Bulking factors are important to predict the potential flow volume and impact area of a watershed in a flood after fire situation. There is no single, agreed upon method for identifying the bulking factor appropriate for a watershed (West Consultants, 2011), or what design event should be used to calculate sediment concentration and bulking factor. Better understanding wildfire processes and debris flow/flood processes can help to inform decision making. Burn severity is recognized to be a principal variable influencing the hydrologic effects of wildfire, so we have focused part of our work on predicting burn severity.

Flow Classification	**Sediment Concentration** by volume (specific gravity = 2.65)	Bulking Factor
Normal Streamflow	0 - 20	0 - 1.25
Hyperconcentrated flow	20 - 40	1.25 - 1.67
Debris/Mud flow	40 - 55	1.67 - 2.5

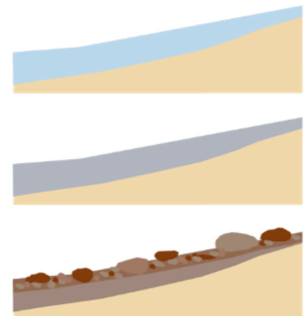


Figure 1: Flow classification by sediment concentration and bulking factors (adapted from Gusman et al., 2009)

Fire Response in Northern vs Southern California

To date, bulking factors have been applied to Southern California, as this region has long experienced wildfires and resulting debris flows, debris floods, and generally higher sediment loads, as a result of the extremely steep topography, easily erodible rocks, and high-intensity rains such as those associated with atmospheric rivers. The phenomenon of “flood after fire” has long been well documented in the San Gabriel Mountains (Munns 1920, DeBano et al 1981), and public works agencies have built debris basins, concrete channels, and other structures to manage the high runoff and sediment loads from burned watersheds. As wildfires occurred predominantly (but not exclusively) in southern California in the 20th century, bulking factors were developed for this part of the state by various agencies (US Army Corps LA District, Los Angeles County Public Works, as well as San Bernardino, Riverside, and Ventura Counties, as reviewed by WEST (2011).

With the increased extent and frequency of large wildfires in northern and central California, CalTrans has recognized the need for methods to estimate bulking factors for northern California (i.e., areas north of Santa Barbara County), which has motivated this study. Unfortunately, there have been few studies documenting post-fire runoff and sediment bulking effects in northern California, so there is still large uncertainty in predicting post-fire effects on runoff and sediment bulking in these parts of the state. As more data are compiled, we anticipate that these relations can be better specified. In the meantime, we can consider factors leading to debris flows and sediment-bulked runoff in general, and how these differ from southern to northern California. Empirically, we can see from the limited data that post-fire runoff response in Southern California tends to be twice that documented in Northern California.

Among the key factors are differences in topography and lithology (rock type and condition), differences in vegetation cover, and intensity of rainfall. The Transverse Ranges of Southern California (e.g. the San Gabriel and Santa Inez Ranges) occur at the ‘Big Bend’ of the San

Andreas Fault system and are thus subject to extreme compression (Crowell, 1979). As a result, these are among the most rapidly uplifting mountains in the world, with uplift rates exceeding 3 mm/y (Johnson et al., 2020). The rocks (predominantly sedimentary in the western Transverse Ranges and granitic in the eastern) are shattered from faulting and tectonic movement, making them highly erodible.

The Southern California hillslopes are dominantly covered by chaparral vegetation, which does not provide consistent shading of the ground surface. When chaparral landscapes burn, they typically burn more thoroughly than the forested slopes characteristic of northern California (DeBano et al 1981), leaving a ‘moonscape’. While there is less vegetation in the chaparral to burn, it’s common to see virtually all of the chaparral vegetation consumed by wildfire. Moreover, severely burned soils under chaparral commonly develop a hydrophobic layer that repels water and leads to increased runoff, which in turn can trigger debris flows.

Rainfalls associated with atmospheric rivers in southern California can be intense. For example, in the Santa Ynez Range above Montecito, rainfalls of over 15 mm over 5 min (3 mm/min) and over 25 mm over 15 min were recorded at two sites during the January 09, 2018 storm (Oakley et al., 2018). When the erodible rocks of these steep mountains are subjected to intense rainfalls, especially after slopes have recently been burned, the result is rapid erosion and mass wasting, including debris flows, as illustrated in Montecito in 2018, and which has occurred repeatedly, with 15 large debris flows documented over the past 200 years in Montecito alone (Serra-Llobet et al., 2023).

By contrast, the landscapes of northern California, while tectonically active, are not so extreme in their deformation rates as the Transverse Ranges. The central California Coast Ranges have uplift rates generally less than 1 mm/y (McGregor and Onderdonk, 2021), still active but not so much as the Transverse Ranges. The lithologies are not typically as shattered as those of the Transverse Ranges (though there are exceptions) and thus tend to be less inherently erodible. The slopes are generally forested, and while there is more fuel loading in the forest, these forested slopes generally do not burn as thoroughly as chaparral slopes. In most cases, there is some remnant of forest trees standing post-fire. These dead trees provide some protection for the soil against intense rains, some slope stabilization, and their roots provide pathways for infiltration. Finally, rainfall intensities are rarely comparable to the extreme rates generated by the steep orographic lift resulting from moisture-laden winds blowing from the sea up the slopes of the Transverse Ranges. Thus, all these factors tend to make debris flow production less likely in northern than in southern California. However, at this time there is little data on bulking of post-fire runoff from northern California burns, and thus inadequate empirical data upon which to base estimates of sediment bulking factors independent of the rich data set available for southern California. Thus, the approach we propose here relies on watershed characteristics first, incorporating factors that influence sediment production statewide.

1.1.1. Research scope

The CalTrans Highway Design Manual (Highway Design Manual: Chapter 810 - Hydrology, 2020) includes an approach to setting bulking factors for post-fire runoff in southern California.

The approach is described in the HDM Section 810, and outlined in a flow chart on pp.810-61 to 810-62 (*Highway Design Manual: Chapter 810 - Hydrology*, 2020). This project builds upon the existing guidance to develop a framework for estimating sediment bulking factors for design of road crossings in northern California.

Our framework includes additional physically-based variables that have become recently available statewide. The deliverables include the narrative report explaining the proposed approach, datasets in ArcGIS that can be readily accessed by district engineers, and a program developed to be a decision-support tool that automatically interrogates statewide data sets for relevant information for a given road crossing site and computes relevant variables, indicating likely flow type, while still requiring the district engineer to use professional judgment to estimate a sediment bulking factor for the site.

1.1.2. Other factors affecting post-fire floods

In addition to increased post-fire sediment loads, post-fire runoff is affected by increased clear water runoff, and non-sediment debris such as large wood and trash. The scope of our project was limited to providing guidance only for assessing *sediment bulking*, but district engineers should be aware of these other factors in the design of road crossings.

Post-fire runoff can be greater than normal runoff due not only to sediment loads, but also due to the altered hydrologic response of soils post-fire. 2-year rainstorms falling on fresh burn scars have been documented to produce runoff 10-30 times higher than would be predicted without the effects of wildfire. But of this increase, the component of bulking potentially attributable to sediment is limited to a bulking factor of 2.0 or 2.5, because of physical limitations in how much sediment can be carried by a given volume of water. The balance of the increase in runoff is attributable to hydrologic effects of reduced infiltration and consequently increased runoff.

Moreover, blockage and/or failure of stream crossings below burn scars is commonly caused by debris jams, as trash, logs, and entire trees can hang up on bridge piers or culvert intakes, trapping further debris, and ultimately plugging the culvert or bridge opening, forcing flow over or around the structure. Woody debris has been a perennial challenge for managers of bridges and culverts generally (Diehl 1997, Lassettre and Kondolf 2012); these challenges become infinitely greater in burned landscapes due to the volumes of woody debris that can be generated and transported into the stream system via debris flows and other mass movements.

Our study has focused only on bulking attributable to higher sediment loads, not the hydrologic effect of increased runoff post-fire, nor the effects of debris accumulation at culverts and bridges.

Road crossings, whether culverts or bridges will always have residual risk to flows beyond their design event. While predictions can be made for the scale of post-fire floods that could occur across culverts and bridges, in many cases it may be unrealistic to construct a culvert or bridge to the dimensions needed to pass the maximum possible bulked flows. In these circumstances, other design techniques can be used to ‘harden’ the road crossing so that even if the crossing is overtopped, the fill prism of a culvert (or the structure of a bridge) is not lost; it may be buried and require excavation post-event, but it can be restored to functionality fairly easily. A simple example would be rocking the fill prism such that an overtopping debris flow will not destroy the crossing, termed a rock-armored 'vented' crossing (Figure 2) (Cafferata et al, 2017). These crossings should be designed with a pronounced dip to effectively convey sediment and debris-charge flows without causing flow diversion or channel avulsion.

Figure 2: Examples of culvert design interventions to manage debris flow (Source: Caffereta et al., 2017. Designing Watercourse Crossings for Passage of 100-Year Flood Flows, Wood, and Sediment (Updated 2017))

1.2. Current Caltrans HDM Guidance

1.2.1. Existing bulking factor estimation process

California Department of Transportation's 2020 Highway Design Manual describes methods to identify bulking factors for debris flow modeling in Chapter 810-Hydrology. The Caltrans Highway Design Manual notes that smaller rain events, such as a 10- or 25-year rain event will require a higher bulking factor compared to larger rain events such as a 100-year storm, as there is a higher concentration of sediment (*Highway Design Manual: Chapter 810 - Hydrology*, 2020). The Highway Manual provides a flow chart laying out how district engineers should identify a bulking factor for their project area. This flowchart defines 6 steps. A simplified version of this flowchart is shown in Figure 3. The first step is for district engineers to identify "relevant watershed data" for their project area, including past debris flow events, geologic maps, soils data, aerial photos, fire history, flood history, seismic/volcanic activity, and watershed geometry. The second step, "field reconnaissance", asks district engineers to identify sediment producing features they can identify on site. The third step, "Debris Flow Likelihood", directs the engineers to consider rock type, slope, and location of site in relation to an alluvial fan. The fourth step asks district engineers to identify flow type and BF based on engineering judgment considering steps 1, 2, and 3 (normal streamflow 1-1.3, hyperconcentrated flow 1.3-1.7, debris/Mud flows 1.7-2.0). The fifth step is to follow the local agency method to calculate debris flow; if the project site is located in a region that does not have a designated method, district engineers are directed to use the LA District Method due to its use of the adjustment-transposition factor. Finally, step six directs district engineers to select a design bulking factor based on: these prior steps, project budget, and highway safety considerations (Highway Design Manual: Chapter 810 - Hydrology, 2020).

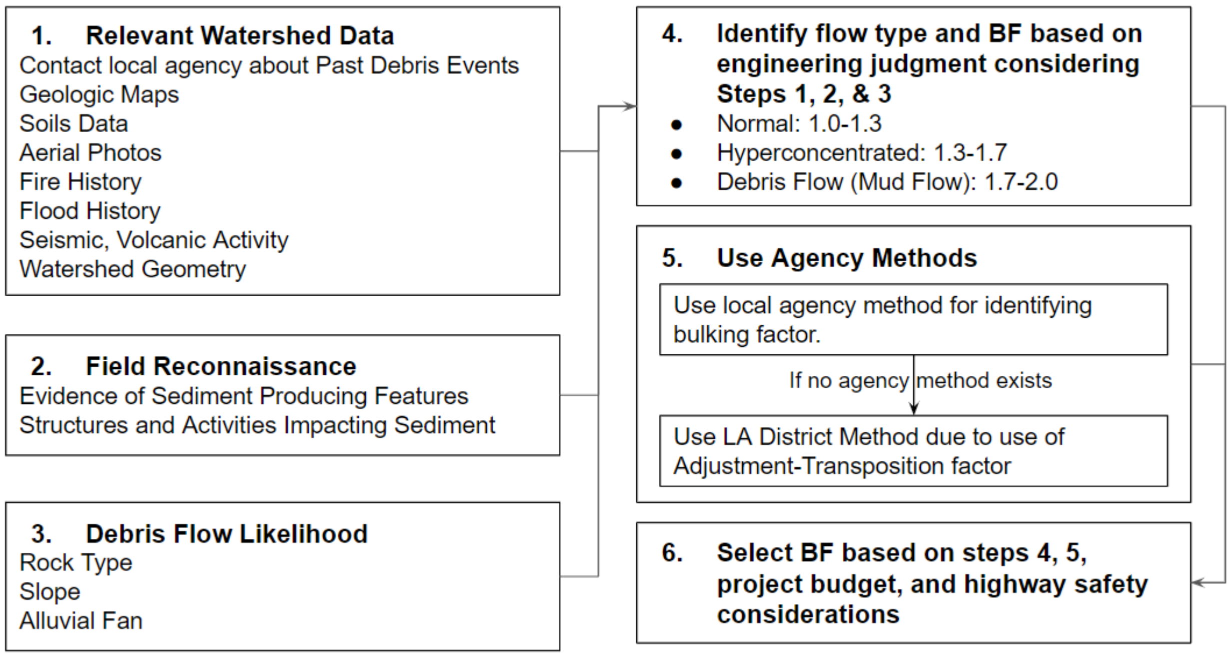


Figure 3: Current methodology given for district engineers to follow in the Caltrans HDM (adapted from Highway Design Manual: Chapter 810 - Hydrology, 2020)

1.2.2. Current limitations of existing process

The current method outlined in the HDM calls district engineers to collect datasets from various sources. The datasets are not compiled nor necessarily easy to find. Providing statewide data sets in a more readily-used format could facilitate the work of the district engineer in determining bulking factors for use in road crossing design. In addition, while the important landscape features and datasets are pointed out in the current HDM, there is no clear path forward for how district engineers should assess these datasets, what thresholds are important within these datasets, and how they should assess these many variables together to identify a single bulking factor. In addition, in the current method, after district engineers are asked to compile data in steps 1 through 3, and determine a flow type in step 4, they are asked to also complete an agency method in Step 5, and finally in step 6 take into consideration their results from both Steps 4 and 5 in addition to project budget and highway safety considerations, to decide upon a single bulking factor. There is a need for an updated method that builds on the current logic and science outlined in the HDM, with more direction on how the variables can be used together to identify an estimated sediment bulking factor.

1.3. How to Use this Report

The purpose of this report is to introduce to Caltrans decision makers and engineers a method for identifying sediment bulking factors for road crossing design with post-fire debris flow risk in mind. The report includes a literature review, proposed bulking factor estimation method, and case studies highlighting practical use of the method. The literature review introduces major concepts behind sediment laden flow and bulking factors to lay the framework for what sediment bulking factors can and can not represent. The proposed bulking factor estimation method provides a step by step walkthrough of the method, the datasets it uses, and a description of each variable used and their thresholds that influence post-fire flows. This method is designed to provide insight and direction in how landscape features and basin geometries can be analyzed to inform probable peak flow types, and estimated bulking factors. The method provides structure for how multiple variables can be assessed together, while requiring engineering judgment. This section also provides insight on the program we created to aid district engineers in gathering, processing, and downloading data for use, as well as aid in completing the analysis quickly. The case study section provides two examples of this method being used: one from Southern California, and one from North Central California. The case studies are provided to help contextualize the method, and the various opportunities for engineering judgment and refinement.

2. Literature Review

Sediment-laden flows are usually distinguished based on the concentration of sediment and its caliber. Flows can behave very differently, from a normal Newtonian fluid (flowing water carrying some sediment) to Non-newtonian flows transporting as much sediment as water. Mudflows and debris flows are perhaps the best known types of sediment-laden flows, both consisting of a flowing muddy matrix capable of suspending larger particles (including boulders). They are distinguished based on the caliber of grains in the flow. If at least half of the grains are larger than sand, it's termed a debris flow, if finer, a mudflow. Both debris flows and mudflows require steep slopes to initiate and to flow, and both eventually 'run out' as they slow on more gentle slopes. In some cases debris flows may come to rest on relatively dry land, where the matrix-supported deposits may 'set up', preserving the distinctive stratigraphy of the debris flow. But more often, the debris flow is followed by water-dominated flow, which can mobilize gravel, sand, and finer grains in the flow and transport them farther downstream, fluvially sorting them in the process, and leaving a distinctively stratified but poorly sorted, framework-supported, deposit. This type of flow is increasingly termed a 'debris flood'.

Church and Jakob (2020) define debris floods as "floods during which the entire bed, possibly barring the very largest clasts, becomes mobile for at least a few minutes and over a length scale of at least 10 times the channel width." The concept of the debris flood is important because downstream of steep mountainous reaches, we are less likely to encounter debris flows themselves and more likely to find debris floods carrying the sediment load farther downstream. Thus many highways are more likely to be exposed to debris floods than debris flows

Various classifications of sediment-laden flows have been proposed, typically ranging from fluvial transport, hyperconcentrated flow (especially with high concentrations of mud), debris floods, mud and debris flows. The types of flow most relevant for post-fire flooding are debris flow, mud flow, and debris flood. Debris flows are defined as a very rapid, to extremely rapid flow of saturated debris in a steep channel with a plasticity index less than 5% (Jakob and Hunger, 2005). If at least half of the grains are larger than sand, the flow is considered a debris flow. Mud flows are finer-grained, defined as a very rapid to extremely rapid flow of saturated debris in a channel with a plasticity index over 5% and significantly greater water content relative to sediment (Jakob and Hungr, 2005). Debris floods are defined as a very rapid flow of water in a steep channel that is "heavily charged with debris" (Jakob and Hungr, 2005). A debris flood has free flowing water present, while still containing floating debris.

In terms of management, a key feature of debris flows is their ability to transport large boulders due to the density of the flowing mud. Boulders are commonly carried in the 'snout' of the debris flow, which is followed by a slurry of mud and debris, and in many cases, by flowing water, still transporting sediment but at lower concentrations (Takahashi 1981). The bouldery snout can be exceptionally destructive of structures it encounters, and individual boulders can exceed the size of openings in bridges and culverts, causing blockages, which can then force flow out of the channel and around the obstruction, potentially destroying the structure in the process.

Church and Jakob (2020) provide a more detailed definition of a debris flood, identifying three types of debris floods based on their triggering mechanisms: 1. A debris flood caused by exceeding a shear stress threshold required for mobilizing D84 bed material; 2. A debris flood caused by dilution of a debris flow; and 3. A debris flood caused by outbreak floods from natural or artificial dams. Church and Jacob (2020) further identify subcategories based on the forces water flow imposes on the bed, but in general define debris floods as a flood where the entire bed, outside of the largest clasts, is mobilized for at least a few minutes and flows downstream a distance that is at least 10 times the channel width. A debris and sediment-laden flow can change between these specific types of flow as it passes downstream in the river system or in one location over time (Church and Jakob, 2020).

There is a specific terminology around the path of the debris flow, starting with the initiation zone, transport zone, and deposition zone (Jakob and Hungr, 2005). Debris flow initiation is often caused by slope failure, generally in areas with steep slopes between 20° to 45°. In these situations, there can be a specific location identified where the debris originated. But post-fire debris flow initiation can be caused by runoff and enhanced erosion from burned slopes. In a post-fire situation, there is an increase in sedimentation rates and runoff rates throughout the burned watershed due to burned biomass, loss of ground cover, and, depending on the fire, hydrophobic soils (McGuire et al., 2021). These conditions also increase the risk of slope failure on top of increased erosion rates.

A great deal of literature on debris flow initiation relates to the failure of colluvial wedges in hilly terrain, where sediment builds up in colluvial hollows (draws) until (usually on a time scale of multiple decades) it fails during an intense rainfall, initiating a debris flow. The US Geological Survey and other agencies devoted a great deal of research effort in the 1970s and 1980s to identifying rainfall intensities that would trigger such failures and debris flow initiation. However, in addition to this classical debris-flow generation mechanism, intense rains on recently burned soils can rapidly run off, bringing large loads of sediment and debris down slopes and into channels. It is this latter mechanism that is of greater interest for our study.

3. Proposed Bulking Factor Estimation Method

3.1. Overview of Proposed Method

The proposed method has five main steps (See Figure 4): (1) Identify the Asset's Coordinates, (2) Delineate Contributing Basin and basin Characteristics, (3) Identify flow type and corresponding bulking factor ranges, (4) Refine the Bulking Factor Estimation, and (5) Calculate Bulking Factor. While this method is a framework that can be processed using geospatial software (e.g., ArcGISPro), we developed a decision-support tool to help streamline and accelerate the GIS processing and calculation steps by generating a bulking factor estimate within minutes. In the Appendix, we provide extensive technical documentation, detailed explanations on installation and implementation, and other relevant metadata and specifications. The case studies in Sections 4.2 were produced using this decision-support tool and we provide the datasets, source code, documentation, and a video explaining how to run the code.

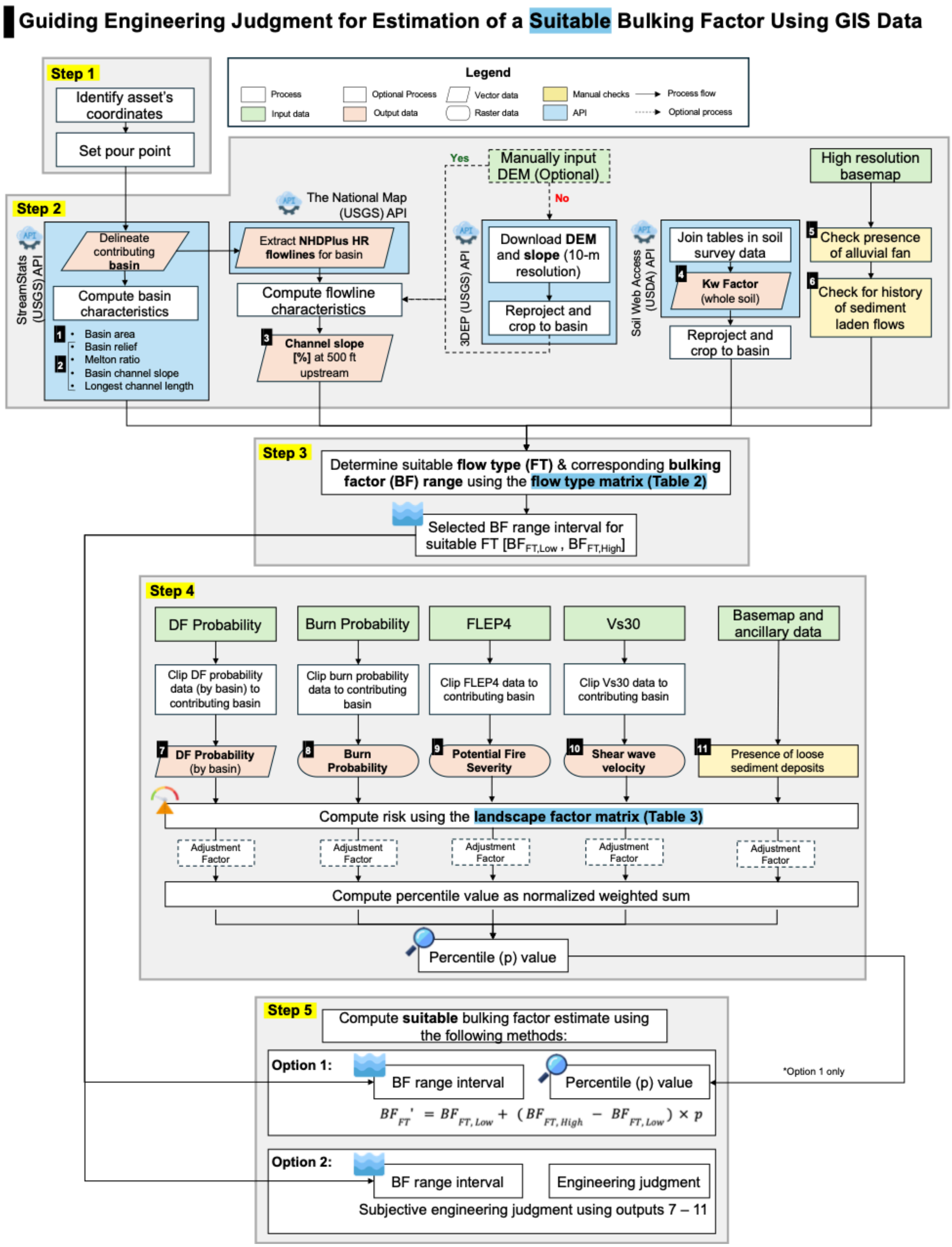


Figure 4. Flowchart of the proposed method

3.2. GIS Datasets and Input Variables

3.2.1 Basin area

Staley et al. (2016) conducted studies of post-fire debris flows in Southern California and the intermontane western US, all of which had contributing basin areas of 0.02 to 8km^2, which is the range seen as most likely to see debris flows. Recently, Ebel (2024) identified an upper limit of basin area for post-fire floods after assessing 61 post-fire debris flows and 119 post-fire floods. While these cases were measured from around the world, the majority were from western United States. This study highlights the importance of contributing basin area in informing magnitude of expected peak flow as well as in informing expected flow type in a post-fire flood scenario. In addition, Ebel (2024) found that while unburned watersheds can have an upper limit of ~100km^2, the upper limit of the basin area for post-fire floods based on an envelope regression estimation was 23 to 34km^2, with a decline with areas >23km^2 according to a power law relation (Ebel, 2024). Cannon et al. (2010) saw similar basin areas in their assessment of 64 post-fire debris flows in the Western United States, none of which had basin greater than 30km^2. Due to these considerations, we use >23km^2, 8-23km^2, and 0.02-8km^2 as the basin area threshold for normal flow, hyperconcentrated flow, and debris flows.

There is an important caveat to consider when using drainage area as a variable, especially for larger basins. There is broad agreement, reflected in research to date (e.g., Cannon et al. 2010, Staley 2016, Ebel 2024) and in comments from the Technical Advisory Committee, that drainage area is an important variable for analyzing debris flow potential. As noted by multiple authors, most debris flows initiate in basins of less than 8 km^2. However, this does not imply that the debris flow vanishes at the point that the drainage area reaches 8km^2. Rather, we see a 'run-out' from the debris flow downstream. Commonly the debris flow will mix with fluvial flow from another tributary and transition into a debris flood (hyperconcentrated flow), which may continue flowing downstream for some distance if the slope is sufficient. The runout from the debris flow/flood may continue downstream to points where the drainage area may exceed 23 km^2, and thus a site whose drainage area exceeds 23 km^2 may still receive a debris flow (or more likely debris flood) from upstream. This is illustrated by our case study on Big Creek (Monterey County) after the Dolan Fire (See Section 4.3).

3.2.2 Channel slope

The slope of the stream channel is important because it tells us about potential runout. As noted in West Consultants (2011), the National Research Council (1996) identified slopes of 10-14% as the downstream limit of higher concentration, coarse debris flows, and 3.5-5.3% as the downstream limit of dilute debris flows. Similarly, and also noted by West Consultants (2011), Stock and Dietrich (2003) identified slopes of 3-10% to be the approximate downstream limit for general debris flows. Taking these factors into consideration, we chose the threshold of a 3% channel slope as defining the end of any potential sediment-laden flows. While runout can occur on upwards of 5 to 10% slopes, we took the lowest slope as our threshold. In our method, slopes above 3% could potentially see any type of flow, and are not limited to normal flow, while slopes <3% are identified as likely to see normal flow. Slope is calculated as a percent by taking the change in elevation divided by the distance (so-called “rise over run”) and multiplying it by 100.

$$S = (dh / dl) \times 100$$

where S is slope as a percent, dh is the change in elevation, and dl is the distance over which the elevation drops.

3.2.3 Melton ratio and watershed length

Wilford et al. (2004) identified the Melton ratio used in combination with watershed length as the most important factors to distinguish between flood, debris flow, and debris flood prone basins. The Melton Ratio is the basin relief divided by the square root of the basin area, while the watershed length is the straight-line distance from the watershed outlet to the most distant point. The basin relief is the difference in elevation between the highest and lowest points in the watershed, and is considered within the melton ratio calculation. Wildford et al. (2004) conducted experiments in British Columbia, Canada and identified class limits that help distinguish what type of flow basins are prone to, with a Melton ratio <0.3 indicating a basin is more prone to normal flooding, a Melton ration between 0.3-0.6 or >0.6 with length >1.677 miles indicates a basin more prone to debris floods, and finally a Melton ratio >0.6 with a watershed length <1.677 miles indicates a basin is more prone to debris flows (Wilford et al., 2004; Jackson, 1987; Bovis and Jakob, 1999). In our method, we compute the watershed length as the largest straight-line distance from the point of interest (where the asset is located) to the farthest located point on the watershed boundary.

3.2.4 Kw factor

As defined in the National Soil Survey Handbook, Kw factor is a soil erodibility factor that quantifies potential soil erosion due to runoff and rain splash. Kw factor considers the whole soil, even larger particle sizes, while Kf factor only considers fine-earth particles less than 2.0mm. Kw factor values range from 0.02 to 0.69, the lower the value the less susceptible to detachment and erosion, the higher the value the more susceptible to detachment and erosion. According to the National Soil Survey Handbook, the most important properties in the K-factor variables are texture, organic matter content, structure size class, and the saturated conductivity of the subsoil. In this method, we direct Caltrans district engineers to use the Kw factor as a variable to help determine potential flow type, as the erodibility of the soils in a contributing basin informs the amount of sediment available for transport. We use the following thresholds for low, moderate, and high erodibility:

$$\text{low} \leq 0.2 \leq \text{moderate} \leq 0.4 > \text{high}$$

(USDA-NRCS-MICH, 2002). While these values have not been directly linked to a flow type, we suggest using these thresholds for normal flow, hyperconcentrated flow, and debris flow for the time being. That being said, the thresholds used can be altered and changed by district engineers based on engineering judgment and new information. In our method, we compute the Kw factor of the dominant component and use the average value found in the contributing basin for subsequent calculations.

3.2.5 Alluvial fans

In general, alluvial fans are evidence from past sediment laden flows of the region of deposition and runout. If the project location for a culvert or bridge is directly upstream of or on an alluvial fan, we can assume that the sediment laden flows that formed the alluvial fan must have passed the site of the culvert or bridge, and that comparable, future flows would likewise pass through the site of the road crossing.

3.2.6 History of sediment laden-flow

Similar to the alluvial fan variable, which is itself lasting physical evidence of a history of sediment laden flow on the landscape, this variable is up to the district engineer to identify and manually define. Outside of alluvial fans, is there evidence of a history of hyperconcentrated or debris flows in the project site? We would not expect to find an alluvial fan form in a canyon (because the canyon wall constriction prevents the flow expansion essential to fan formation), so we must look for other evidence of past flows. These could include maintenance records, news articles of past debris flows at the site, other field evidence, or anecdotal reports from residents or experienced engineers (who may be retired but available to share their experience). If there is no evident history of sediment laden-flows, that does not necessarily rule out past events. Rather, in assessing the potential for sediment-laden flows, this variable can be skipped (as 'ND', no data). If there is a known history, this variable will add more value to hyperconcentrated or debris flow.

3.2.7 Debris flow likelihood model

The Post-Fire Debris Flow Likelihood (PFDFL) data is created by using the logistic model developed in Staley et al. (2016), which integrates slope (>23 degrees), soil burn severity (moderate and high via differenced Normalized Burn Ratio), and soil erodibility (rock-free K-Factor). While the training dataset used in Staley et al. (2016) is predominantly from southern California and may overestimate risk in Northern California, we assume that the PFDFL dataset can be a useful measurement to help gage a level of risk. California Geological Survey (CGS) has identified classified probabilities within the PFDFL data, dividing the probability percents by equal intervals across five classes from 1 to 5; 1 = 0-20%, 2 = 20-40%, 3 = 40-60%, 4 = 60-80%, and 5 = 80-100%. In discussion with CGS, and following their categorization of debris flow likelihood, we use the following thresholds for low, medium, and high probability of debris flows: $P<40\%$, $40\% \leq P < 60\%$, and $P>60\%$, with the classified probability groups 1 and 2 being low, 3 being medium, and 4 and 5 being high. We use the PFDFL predictions for 15-min 24mmh at basin scale and average them to generate a single value for subsequent calculations. PFDFL predictions are made by USGS after major fires using observed burn severity data, but these are limited to areas that have already burned. To allow for future predictions to be made ahead of potential wildfires, CGS has created a synthetic burn severity dataset for the state, and a predictive PFDFL dataset for the state. We recommend using this dataset created by CGS for this analysis in order to assess possible bulking factors in areas that have not yet burned.

3.2.8 Burn probability

Following a wildfire, burned fuels and debris can lead to hydrophobic soil conditions and an increased risk of debris flow when triggered by intense rainfall (Jakob et al., 2005). To account for the likelihood of a fire occurring and the potential to increase debris flow risk, we use burn probability computed from thousands of stochastic simulations of various fire-climate scenarios using a physics-based fire spread simulation model called Fire Simulation (i.e., FSim) (Finney et al., 2011) provided as statewide datasets by the USFS (Short et al., 2020; Scott et al., 2024). Burn probability represents an annual likelihood of a fire's occurrence at a given location (i.e., chance of burning in any given year) and is a function of vegetation and wildland fuels from LANDFIRE, historical fire data, terrain, and weather parameters. The burn probability dataset is produced at 270m spatial resolution and upsampled to 30 m, and for California, annual burn probability ranges from 0 to 12%. We use thresholds of 0-5%, 5-10% and >10% as ranges for low, moderate, and high burn probability ranges. Further, we average the burn probability values in the contributing basin for subsequent calculations.

3.2.9 Potential fire severity

The amount of moderate to high severity burn is a key variable in many post-fire debris flow likelihood models that connects wildfires and subsequent debris flow occurrence. As a proxy measure of potential fire severity, we used 4ft flame length exceedance probability (FLEP4) data produced as an output from FSim (Finney et al., 2011), which represents the likelihood a given location will have flames larger than 4 feet in length (Short et al., 2020; Scott et al., 2024). Yu et al. (2023) used FLEP4 with burn probability to model the probability of wildfires causing moderate to high severity burns in regional watersheds. This metric ranges from 0 to 100% and we use thresholds of 0-25%, 25-50% and >50%. Further, we average the FLEP4 values in the contributing basin for subsequent calculations.

3.2.10 Shear wave velocity in the upper 30m (Vs30)

Shear wave velocity is a measure of the speed at which body waves move through the earth. This velocity is dependent upon the characteristics of the rock and soil, such as particle density, bulk density, packing arrangement, number of particle contacts, and ambient stress conditions (Moss and Lyman, 2022). Shear wave velocity has long been used to predict impacts of seismic shaking, and liquefaction, looking at how stiff, or solid rock and sediment are and how resistant they may be or prone they may be for liquefaction. The higher the velocity, the denser the sediment is, while the lower the velocity the looser the sediment is leading to it being more prone to liquefaction, lateral spreading, flow failures, and other ground failures (Moss and Lyman, 2022). Moss and Lyman (2022) test the use of Vs30 as a proxy for sediment shear stiffness in the Staley debris flow likelihood model, replacing Kf factor with Vs30 to see how this variable impacts prediction reliability. They found that Vs30 variables provide similar results as the original Staley method which uses the Kf factor, showing the potential of Vs30 to inform debris flow predictions. Wills et al. (2015) created a shear wave velocity dataset for California which we use in our method to inform soil and rock conditions. The range of Vs30 values in this dataset for California is 0-733.4 m/s. There are no standard thresholds for determining low, moderate, or high shear wave velocity. We use 0-250, 250-500, and >500 m/s as ranges for low, moderate, and high Vs30 ranges, with the higher ranges relating to more stable soils and rocks with less vulnerability to failure. These thresholds can be modified by the district engineer. In our method, we use the updated Vs 30 dataset provided by Thompson (2018) which provides data at a higher resolution of 3 arcseconds instead of 7.5 arcseconds. We average the Vs30 values in the contributing basin for subsequent calculations.

3.2.11 Presence of Loose Sediment

Presence of loose sediment deposits in a contributing basin means there are easily erodible sources of sediment that can bulk flows. Examples of such deposits include landslides, mass wasting, alluvial fans, debris basins, reservoirs, elevated railroad beds, and mining operations. In this method, the presence of loose sediment is a variable assessed by the district engineer who will determine if there are loose sediment deposits, and if so, decide if the amount of loose sediment deposits will likely impact the bulking or not. If “Yes”, that means the sediment deposits are likely to impact flow and will direct the district engineer towards the higher end of the bulking factor range. This variable can also be left out of the assessment and not influence bulking factor refinement if there are no or so little sediment deposits it is unlikely to impact flow, or if district engineer choses to leave it out. Reasons for the variable to be left out may include lack of sufficient data, or lack of confidence in the data. Assessment of this variable may require a site visit to the contributing basin, and/or a desktop assessment of aerial images, landslide databases, mining databases, railroad databases, or other data depending on how the district engineer choses to do their assessment.

3.2.12 Limitations of Using Ancillary Data Generated By Third Parties

There are a number of caveats to consider when using spatial data generated by third parties. For example, a 30 meter DEM from a USGS data site will simplify the slope of a stream channel and may bias the variables generated from this data. This is a common problem of data fusion where data is coming from various third parties who generated it under different specifications to solve unrelated problems. DEMs are a good example of this as they often range from 1 to 30 meter resolution. In this example, our process and facilitating software allows for the substitution of higher spatial resolution input data, such as a DEM generated from Lidar, to be integrated into the solution if an engineer, from field observation, feels the downloaded DEM from the USGS does not best represent the surface used to calculate the slope of a stream channel.

Each year the gathering and processing of data measuring the landscape is becoming more accurate and better at representing the physical characteristics of the earth. In short, the GIS based data is becoming available at higher spatial resolutions. As a result, the calculation of bulking factor estimates will likely improve over time using our method.

3.3. Spatial Analytical Process Using GIS data

3.3.1. Step-by-step walkthrough

Step 1. Identify Asset's Coordinates
The first step for the Caltrans District Engineer is to identify the coordinates of their asset or road crossing.

Step 2. Delineate Contributing Basin and Basin Characteristics
The second step is to delineate the contributing basin for the asset and the basin's key characteristics: relief, area, slope, watershed length, and Melton Ratio. Once the basin is delineated and a shapefile is created for the basin, the district engineer will be able to download all needed data for the basin region itself.

Step 3. Identifying flow type and corresponding bulking factor ranges
The third step is to identify expected peak flow type, which will give district engineers a bulking factor range to work with. We have identified six variables for use in informing expected peak flow type at the project location: 1. Basin area, 2. Channel slope, 3. Melton Ratio with Watershed Length, 4. Soil erodibility Kw factor (Table 2), 5. presence of an Alluvial Fan at project location, and 6. history of sediment laden flows. In this method, each variable (v_i) has thresholds corresponding to an expected flow type: normal flow, hyperconcentrated flow, or debris flow. District engineers will assess all six variables in their project basin and what peak flow type each variable directs them to. The average is then calculated to identify probable flow type for the project location considering all six variables. To calculate the average flow type of all six variables, a score (α_i) is given to each variable based on if that variable's threshold points to normal flow, hyperconcentrated flow, or debris flow. A score of 1 is given to normal flow, a score of 2 is given to hyperconcentrated flow, and a score of 3 is given to debris flow.

Table 1: Scores allocated to each flow type and corresponding bulking factor range

Score (α_i)	**Flow type**	**Bulking Factor Range** *Upper and lower bound values can be changed
1	Normal flow	0 - 1.25*
2	Hyperconcentrated flow	1.25 - 1.67*
3	Debris flow	1.67 - 2.00*

Once scores are given to all six variables, the average is calculated to identify the final flow type score for the project location. This is done by dividing the sum of the scores by the total number of variables. In some situations, it is possible that not all variables will be used in the assessment, if that is the case the total number of variables can be less than 6. Three of the variables, channel slope, presence of an alluvial fan at project location, and history of sediment laden flows, have the potential to direct one to "any flow type possible", in which case that variable will not be considered. Once the average score is identified, it is used to determine the estimated peak flow type. The standard procedure is to round the final averaged score to the closest integer: 1 meaning normal flow, 2 meaning hyperconcentrated flow, and 3 meaning debris flow; and then use the expected BF range for that flow type. But, if a district engineer gets a final score of, say, 2.5, and wants to use a BF range between hyperconcentrated and debris flow instead of rounding directly up to debris flow, they can choose to do that.

$$Flow\ Type = \frac{1}{n}\sum_{i=1}^{n} \alpha_i$$

Table 2. Variables and thresholds for determining suitable flow type and bulking factor range. The bulking factor range shown in the table is retrieved directly from the HDM.

#	**Flow Type**	**Any flow type possible**	**Normal Flow**	**Hyperconcentrated Flow/ Debris flood**	**Debris Flow**
	Bulking Factor Range (E.g., HDM)	**-**	**0 - 1.25**	**1.25 - 1.67**	**1.67 - 2.00**
	Score for Normalized Sum Calculation	**-**	**+1**	**+2**	**+3**
1.1	**Area of Basin**	-	>23km^2	8 - 23km^2	0.02 - 8km^2
1.2	**Channel Slope (500ft upstream of asset)**	≥3%	<3%	-	
1.3	**Melton Ratio and Watershed length**	-	Melton <0.3	Melton 0.3-0.6; or >0.6 with watershed length >1.677 mi	Melton >0.6 with watershed length <1.677 miles
1.4	**Kw Factor**	-	≤0.20	>0.2;≤0.4	>0.4
1.5	**Alluvial fan** ***Manual entry**	None	-	Upstream / on	
1.6	**History of Sediment laden flow** ***Manual entry**	Unknown/None	-	Yes	

Example:

For instance, these are the scores each variable would get with the following site conditions: (1) Area of basin of 8-23km^2, this variable will get a score of 2; (2) a channel slope greater than 3%, you will ignore that variable and not include it in the average as this threshold directs you to any flow type; (3) a Melton ratio >0.6 with a watershed length <1.677miles, this variable will get a score of 3; (4) has a Kw factor between 0.2 and 0.4, this variable will get a score of 2; (5) is on an alluvial fan, this variable will get a score of 3; and (6) has a history of sediment laden flow, this variable will get a score of 3. In this scenario, five variables are used, and you have scores of 3, 2, 3, 3, 2. The sum of all these variable scores is 13. Divide this sum by the total number of variables, 5, which gives you the average, 2.6. This average rounded to its closest integer is 3, directing you to a debris flow as the peak probable flow type based on these landscape features. The district engineer can decide the bulking factor range based on this probable flow type information.

Step 4. Refine the Bulking Factor Estimation

Once a probable flow type is identified in Step 3 and the district engineer has a Bulking Factor range, they must decide which value within the selected range is appropriate for use at their site. Step 4 leads the user through five variables that can inform the scale of sediment bulking in a basin. The five variables (x_i) are: 1. Post Fire Debris Flow Likelihood (PFDFL), 2. burn probability, 3. potential fire severity, 4. Shear wave velocity (Vs30) in basin, and 5. Presence of loose sediment deposits in basin (Table 3). The first four variables are connected to spatial datasets that are automatically created for the study area when using the program developed for this method. The fifth variable must be researched by the district engineer and manually entered.

In Step 4, a method is laid out for combining these variables as a weighted average, and then using the result as a percentile for identifying a bulking factor in Step 5. The district engineer can use this quantitative method to assess these variables, or can choose to assess the variables using engineering judgment to decide on the bulking factor in Step 5, or a combination of both.

The conceptual logic behind this step is similar to the calculation for the flow type in Step 3; however, since we have already identified the flow type and therefore the bulking factor range, here, each variable is given a threshold defining low, medium, and high risk as opposed to flow type. Adjustment factors can be used to change the risk value higher or lower based on engineering judgment (adjustment factors less than 1 lower the risk of that variable, adjustment factors over 1 increase that risk). Then, we consider the average of the *weighted* sum of the variables and use the resulting value as a *percentile* to calculate a specific Bulking Factor from the range identified in Step 3.

Our method assesses each variable (x_i) and records a score (β_i) based on thresholds of “risk” defined in Table 2:

$$\beta_i = \begin{cases} \mathbf{1}\ if\ Low\ Risk \\ \mathbf{2}\ if\ Moderate\ Risk \\ \mathbf{3}\ if\ High\ Risk \end{cases}$$

Similarly to Step 3, we use integer values of 1, 2, and 3 for the scores, though these scores represent low, medium, and high risk of sediment laden flows instead of flow type. These scores are calculated for all "*n*" variables based on the thresholds shown in Table 3. To further refine the estimation, users have the option to add adjustment factors (w_i) to each of the variables. These adjustment factors can be set by the district engineer if they want the scores to be lowered or raised due to site knowledge, or specific site conditions the datasets are not sensitive to, thus providing a flexible parameter for further engineering judgment. The adjustment factors can be any value between 0 and 3. Once each variable is given a score, and multiplied by their adjustment factor, they are combined as a weighted sum then divided by the total number of variables to find the average. This average is then divided by the highest possible score (β_{max}) to normalize the result and make it into a percentile (p) from 0-1 as described in the following equations:

$$A = \frac{1}{n}\sum_{i=1}^{n} w_i \times \beta_i$$

$$p = \frac{A}{\beta_{max}}$$

Where:

A is the average of the weighted sum

n is the total number of variables included in the assessment

w_i is the adjustment factor (weight) for each variable

β_i is the score for each variable

p is the percentile as a value between 0 and 1

β_{max} is the highest score possible, which is 3 in this method

These two equations can be simplified into one equation as shown below. Here we find the percentile (p) directly by calculating the normalized average of the weighted sum.

$$p = \frac{1}{n \times \beta_{max}}\sum_{i=1}^{n} w_i \times \beta_i$$

The resulting percentile (p) will be a number between 0 and 1, and can then be used as a percentile to identify a refined bulking factor in Step 5. 1 is the maximum value for the percentile. If the percentile is anything above 1, it will be set to 1.

Table 3. Variables considered for bulking factor refinement. Weights are shown as uniform in the table, but are modifiable as long as the sum of all adjustment factors equals the total number of variables used.

#	Feature	Adjustment Factors	Low (+1)	Moderate (+2)	High (+3)
2.1	**Post-fire debris flow likelihood (P)**	w_1	P < 40%	40% ≤ P < 60%	P > 60%

2.2	**Burn probability**	w_2	P < 5%	5% ≤ P < 10%	P > 10%
2.3	**Potential fire severity (FLEP4)**	w_3	P < 25%	P ≤ 25% < 50%	P > 50%
2.4	**Vs30m shear wave velocity to 30m depth (1:24,000 scale)**	w_4	>500 m/s	250-500m/s	<250 m/s
2.5	**Presence of Loose Sediment deposits in basin** ***Manual entry**	w_5	-	-	Yes

Example: We can calculate the percentile for a site with the following conditions where we use an equal weighting of 1 for each variable: 2.1 Post-fire debris flow likelihood of 40% ≤ P < 60%, would be a score of 2; 2.2 Time since last fire <10, would be a score of 1; 2.3 burn probability of 50, would be a score of 2; 2.3 Potential fire severity of high, would be a score of 3; 2.4 Shear Wave velocity of 250-500m/s would be a score of 2; and 2.5 Presence of loose sediment determined to be moderate, would be a score of 2. Here we use all six variables with weighted scores of 2, 1, 2, 3, 2, 2, the sum of which is 12. Plugin this into the equations above, we get 2.4 for the average weighted score, and 0.8 for the percentile.

$$A = \frac{1}{5}12 = 2.4$$
$$p = \frac{2.4}{3} = 0.8$$

Step 5. Calculate Bulking Factor

In Step 5 you identify the refined bulking factor value (BF_{FT}') from the BF range identified in Step 3. In step 5 the user can use engineering judgment to assess the variables and result of step 4, and identify a bulking factor for themselves, or they can directly use the equation provided. The normalized average of the weighted sum from Step 4 is a percentile (p) used for relative scaling. The percentile (p) from Step 4 informs you on how severe the sedimentation may be in your project location based on the landscape features and conditions. Find what that percentile (p) is in your bulking factor range ($BF_{FT,Low}$ to $BF_{FT,High}$) to identify an estimated bulking factor. You can use the following equation to identify what that refined bulking factor (BF_{FT}') would be:

$$BF_{FT}' = BF_{FT,Low} + (BF_{FT,High} - BF_{FT,Low}) \times p$$

where:

BF_{FT}' is the refined Bulking Factor value

$BF_{FT,Low}$ is the minimum value in the BF range

$BF_{FT,High}$ is the maximum value in the BF range

p is the desired percentile

Example: If your expected flow type is Debris Flow, and your BF range is 1.67-2.00, and your average weighted sum from Step 4 is 2.4, which is 80% of 3, then your normalized average weighted sum is the percentile (p) 0.8, and your final BF value will be the 0.8 percentile of 1.67-2.00 which is a bulking factor of 1.93, as shown in the following equation:

$$BF_{FT}' = 1.67 + (2.00 - 1.67) \times (.8) = 1.93$$

As the decision maker, I may choose to use the bulking factor calculated: 1.93, or I may choose to take this as a consideration, and alter it based on engineering judgment.

3.3.2. Data collection

(1) Input data

Statewide datasets are downloaded and can be stored locally while very large datasets (eg. high resolution DEMs and slope raster datasets) are not stored locally. Instead, we download these large datasets in real-time from their corresponding web service as preprocessed datasets for a specific region of interest (e.g., case study of a basin of interest). In Table 4, we organized these datasets and their applications in deriving variables used in our method. We also show their file formats and original data sources. To note, the "Deliverable" column indicates the "statewide" datasets shown below in Figure 5, and are provided together with the coded program. "Case study" datasets are downloaded and preprocessed in real-time using the APIs for specific basin extents. For users who do not use the coded program, DEM, slope, and Kw Factor can be obtained from their respective original sources, as linked in Table 4.

Table 4. Main datasets used in our coded program

#	Statewide Dataset	Applied Variables	Format	Deliverable	Original Source
1	DEM	• 3.2.1: Basin area • 3.2.3: Melton ratio	Raster (.tif)	Case study	USGS
2	Slope	• 3.2.2: Channel slope	Raster (.tif)	Case study	USGS
3	Slope [%]		Raster (.tif)	Case study	USGS
4	Kw Factor	• 3.2.4 Kw Factor	Shapefile (.shp)	Case study	USDA (SSURGO)
5	Burn probability	• 3.2.9: Burn probability	Raster (.tif)	Statewide	USFS
6	Potential fire severity	• 3.2.10: FLEP4	Raster (.tif)	Statewide	USFS
7	Shear wave velocity	• 3.2.11: Vs30	Raster (.tif)	Statewide	USGS (Thompson, 2018)

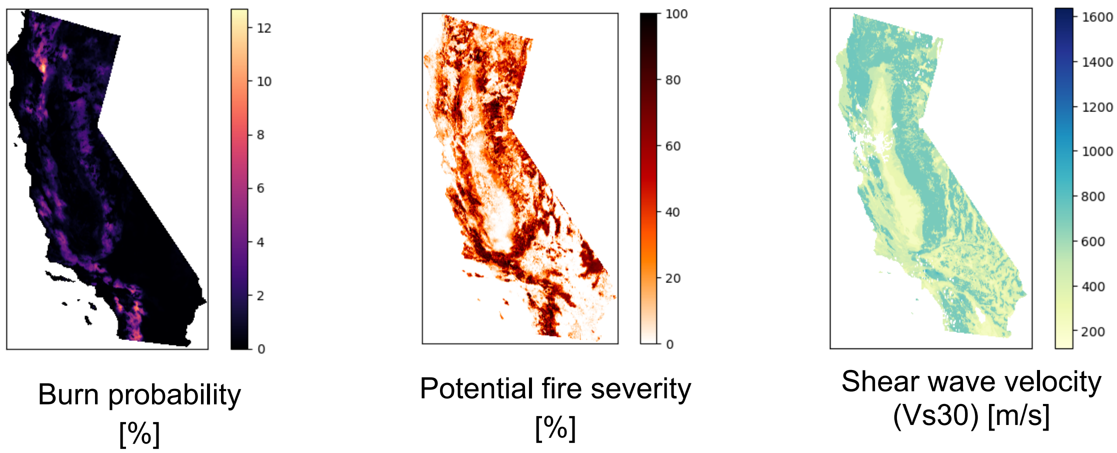


Figure 5. Provided statewide datasets

(2) Case study data

Aside from statewide datasets, for case studies, we also need datasets and information regarding specific regions of interest (i.e., contributing basin). These datasets include point information (i.e., latitude and longitude) of the asset of interest and PFDFL data (See Section 3.2.7). PFDFL data is computed for a select number of past wildfires as part of emergency assessments of post-fire debris flow hazards by the Landslide Hazards program in USGS. PFDFL data can be accessed on their website: https://landslides.usgs.gov/hazards/postfire_debrisflow/.

Users can input a preprocessed or refined shapefile of the contributing basin to substitute for the automatically generated one by the StreamStats API. Similarly, a preprocessed or refined shapefile of the flowlines can also be inputted to substitute for the flowlines extracted from the NHDPlus high resolution dataset. This substitution is important when automatically extracted shapefiles of the contributing basin and their flowlines may not be fully representative or accurate.

(3) Application Programming Interfaces (APIs)

We use Application Programming Interfaces (APIs) in the program we developed to help ease and accelerate data collection, as shown in Table 5. We used the StreamStats API to delineate the contributing basin, compute basin characteristics, and compute flow statistics. In addition, we use *HyRiver*, an established Python package designed with APIs to web services, for the collection of large hydrology and climatology datasets (Chegini et al. 2021). First, we use this package to obtain up to 12 different topographic data variables from 3DEP web services. Our program specifically uses this package to download DEM, slope (measured in degrees), and slope percentage, which are automatically downloaded, reprojected, and cropped to the given extent and coordinate reference system. Second, we use this package to download flowline data from The National Map web services. We use the NHDPlus high resolution flowlines dataset, which is available statewide and was built using the National Hydrology Dataset High

Resolution data at 1:24:000 scale, 3DEP topographic data at 10-m resolution, and the Watershed Boundary Dataset. The NHDPlus high resolution flowlines is an upgrade over the previous version (NHDPlus Version 2), providing much more detail and millions of additional flowline vector features. Lastly, we use *pysda*, a public python package included as a part of the USGS' National Cooperative Soil Survey's collection of repositories. We use this package to query and access soil survey data (Kw factor) from the Soil Data Access web services provided by USDA's Natural Resources Conservation Service.

Table 5. Main datasets from global datasets (see Table 4) acquired via APIs

API	Usage	Source
py3DEP (HyRiver)	DEM and slope	https://github.com/hyriver/py3dep
pyNHD (HyRiver)	NHDPlus High resolution flowlines	https://github.com/hyriver/pynhd
pysda	Kw factor from SSURGO	https://github.com/ncss-tech/pysda/

3.3.3: Data outputs

Our program outputs raster (.tif) and vector (.shp) GIS datasets at the basin and channel scale. All rasters are produced using a coordinate reference system of NAD83 / Conus Albers (EPSG code: 5070) to facilitate measurement calculations and minimizes distortion by facilitating a projection for the entire state. Vector shapefiles are also provided in NAD83 / Conus Albers.

Table 6. Output GIS datasets

Variable	Units	Format	Download Method	Dataset Source
DEM	m	Raster (.tif)	Downloaded via web services API Chegini et al. (2021)	USGS
Slope Percent (basin)	%			
Slope Degrees (basin)	Degrees			
Slope Percent (channel)	%			
Slope Degrees (channel)	Degrees			
Vs30	m/s		Thompson, E.M., 2018	
Burn probability	%		Scott et al., 2024	USDA
FLEP4	%		Scott et al., 2024	USDA
Contributing basin	-	Shapefile (.shp)	Downloaded via web services API (StreamStats)	USGS
Point of interest	-		-	-
Upslope channel at 500ft	-		-	-
Flowlines	-		Downloaded via web services API Chegini et al. (2021)	USGS
Kw factor	-		Downloaded via web services API (SSURGO)	USDA
Summary table of results	-	Comma separated values (.csv)	-	-

4. Case Studies

4.1. Background and Purpose of Case Study Application

We chose two case study sites to run this method on as examples of the workflow. One site is the Murphy Creek culvert in the 2021 Dixie fire footprint along the Feather River in Plumas County, California. The post-fire flood occurred in November, 2022 and overwhelmed the culvert. The other site is the Big Creek bridge in the 2020 Dolan fire footprint along Big Creek in Big Sur, California. The post-fire flood occurred in January 2021, but the bridge was not damaged. We have chosen these locations to run a preliminary pilot study and show what this method looks like when used to specify the bulking factor for a culvert and a bridge.

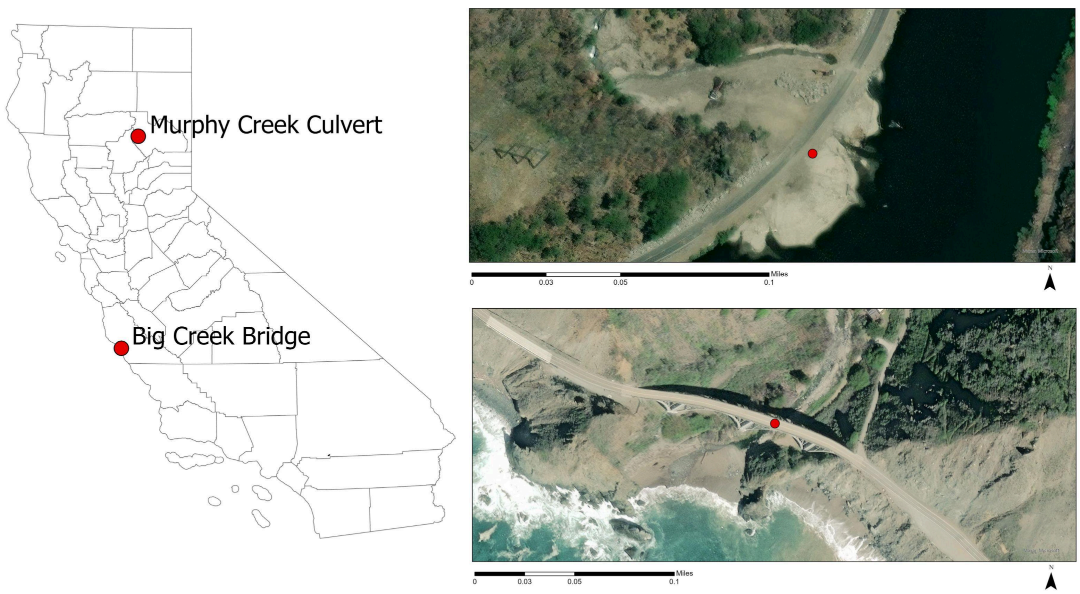


Figure 6. Case Study locations: Murphy Creek culvert and Big Creek bridge

4.2. Assessing Murphy Creek, Hwy 70

Step 1. Identify Asset's Coordinates

Step 1 is to identify the asset's coordinates. Murphy Creek culvert along Route 70 is located at 121.2804053°W 39.9918156°N. The post fire flood brought debris down through the tributary and took out the culvert, as can be seen in the aerial image of the site in Figure 7.

Figure 7. Murphy Creek Culvert

Step 2. Delineate Contributing Basin and Basin Characteristics

Step 2 is delineating the contributing basin, and gathering the data that describe the basin characteristics. In this step we generate the base GIS datasets needed to compute the variables required for expected flow type estimation and bulking factor refinement in Steps 3, 4, and 5. First, we extract the contributing basin using the StreamStats API and compute basin characteristics and flow statistics (Figure 8). Then, we compute the DEM and slope datasets from the 3DEP API (Figure 9). We have the option of downloading these datasets and opening them in ArcPro ourselves, or running the analysis through the program provided. Once we know the contributing basin and have its shapefile, we can download all the data necessary for our basin that will be used in the following steps.

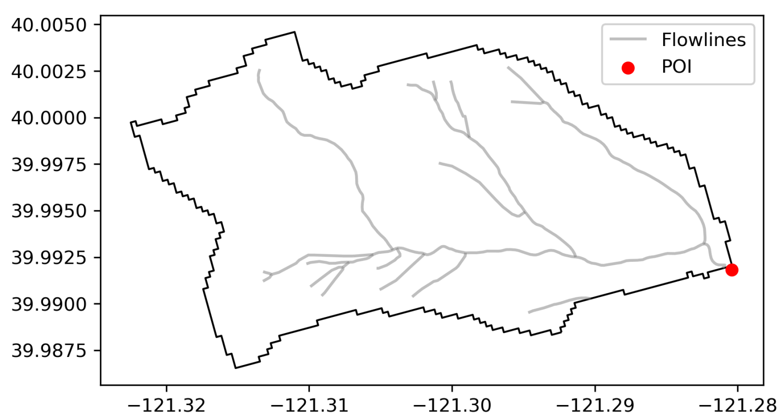


Figure 8. Basin and flowline characteristics calculated using the StreamStats API

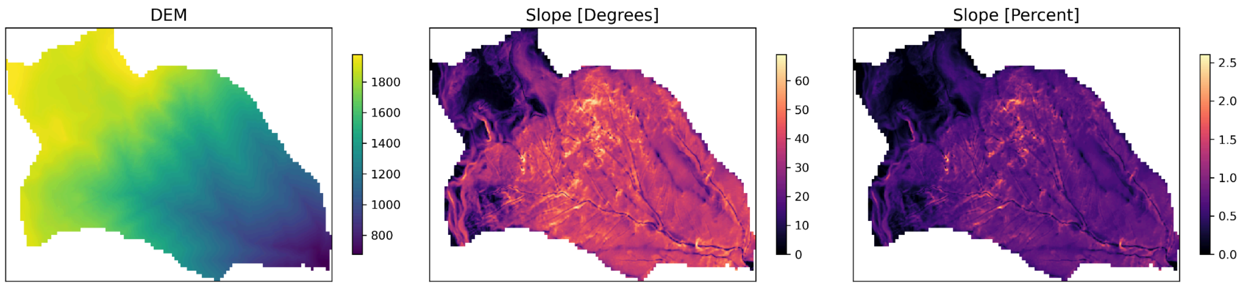
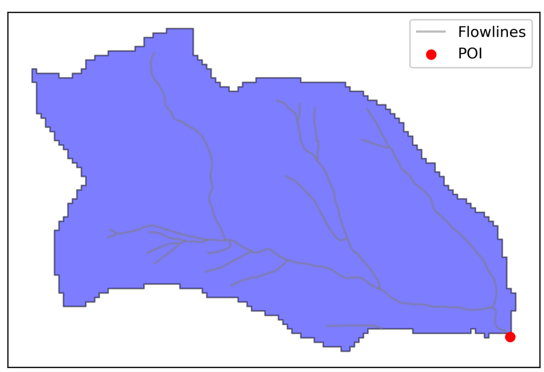


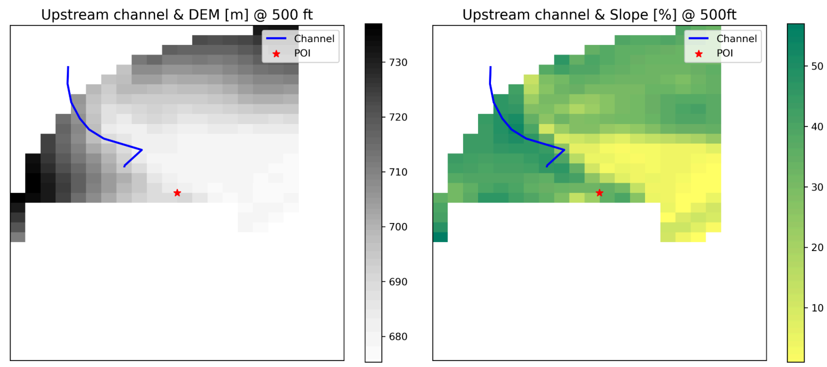
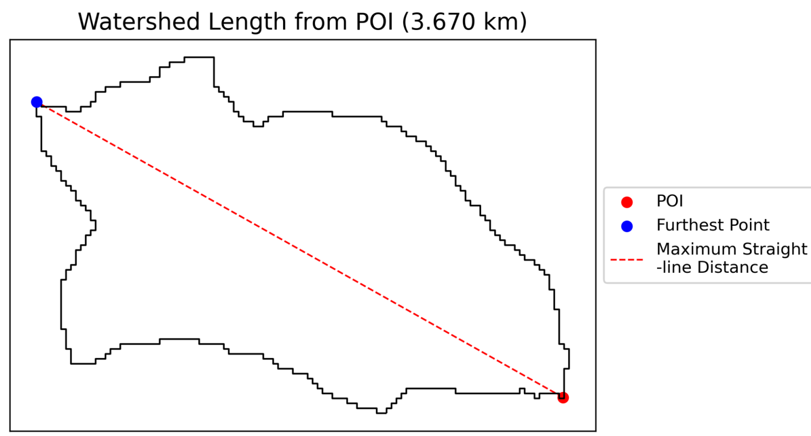
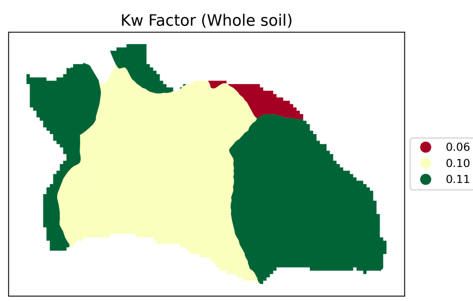
Figure 9. Topographic data clipped to the contributing basin

Step 3. Identifying flow type and corresponding bulking factor ranges

In Step 3 we identify the probable peak flow type for Murphy Creek culvert. We gather the data for each of the six variables used to determine probable flow type: 1. Basin area, 2. Channel slope, 3. Melton ratio and watershed length, 4. Erodibility Kw factor, 5. Alluvial Fan, and 6. History of sediment laden flow. Spatial datasets are used to assess the first four variables, but the last two variables: the presence of an alluvial fan and history of sediment laden flow, is determined by the user and requires a manual entry. When using the program we developed, the spatial datasets are automatically downloaded, preprocessed and stored to your local machine and can be visualized as shown in Table 7.

Table 7. Variables used in Step 3 for Murphy Creek and a visualization of the datasets produced by the program

#	Variable	Visualization
3.2.1	Basin area	

3.2.2	Channel slope	
3.2.3	Melton ratio and watershed length	
3.2.4	Kw Factor	
3.2.5	Alluvial fan	Manual
3.2.6	History of sediment deposits	Manual

An assessment of these variables can be seen in Table 8. The basin area is 4.39km^2 , which falls within the threshold for a debris flow, with a score of 3. The Channel slope is 37.28%, which falls within the threshold of any flow type possible, meaning this variable is not considered. The melton ratio is 0.62 and the watershed length is 3.67km, which falls within the threshold for a hyperconcentrated flow, with a score of 2. Kw factor is 0.1, which falls within the threshold of normal flow, with a score of 1. Manual assessment of the presence of an alluvial fan at the project location was that the culvert was in fact on top of an alluvial fan, which falls within the threshold for either hyperconcentrated or debris flow, with a score of 3. The final variable, history of sediment laden flow, was unknown, leading to this variable not being considered. In total, 4 of the 6 variables were used in this case.

Table 8. Results of the Step 3 Murphy Creek Culvert Variable Assessment

#	Flow Type	Any Flow Type Possible	Normal Flow	Hyperconcent -rated Flow	Debris Flow	Results
	Bulking Factor Range (E.g., HDM)	**-**	**0 - 1.25**	**1.25 - 1.67**	**1.67 - 2.00**	
	Score for Normalized Sum Calculation	**-**	**+1**	**+2**	**+3**	
3.2.1	Basin area	-	>23km^2	8 - 23km^2	0.02 - 8km^2	4.39 km^2
3.2.2	Channel Slope (500ft upstream of asset)	≥3%	<3%	-		37.28%
3.2.3	Melton Ratio & Watershed length	-	Melton <0.3	Melton 0.3-0.6; or >0.6 with watershed length >1.677 mi	Melton >0.6 with watershed length <1.677 miles	0.62 & 3.67 km
3.2.4	Kw Factor	-	≤0.20	>0.2;≤0.4	>0.4	0.10
3.2.5	Alluvial fan	None	-	Upstream / on		Yes
3.2.6	History of Sediment laden flow	Unknown/None	-	Yes		None

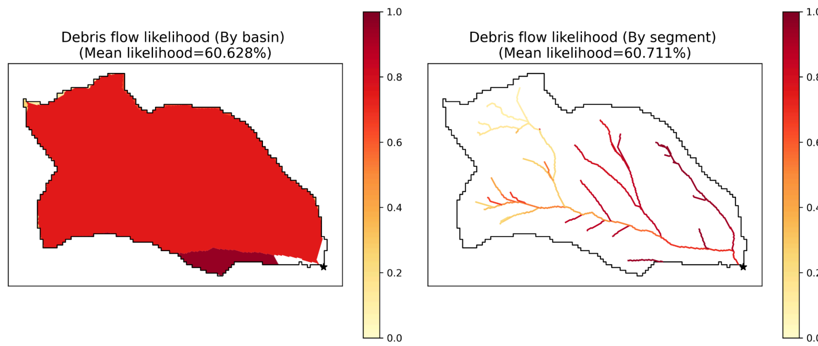
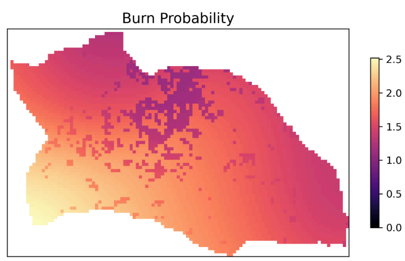
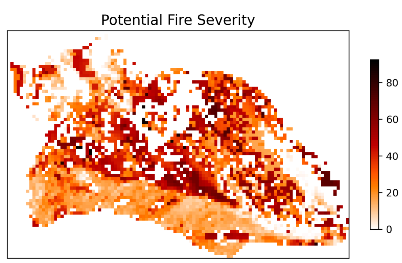
The average of these scores is then calculated to identify the flow type and corresponding bulking factor range interval. The average score for this site is 2.25, which is rounded down to 2, which directs us to expect a hyperconcentrated flow. In this assessment we are considering a Q100 event, and use a bulking factor range of 1.25-1.67 for hyperconcentrated flows. The calculations for this can be seen below. When using the program we developed these calculations will be done automatically once all the variables are set, but the calculation can be done manually as well if preferred by the district engineer.

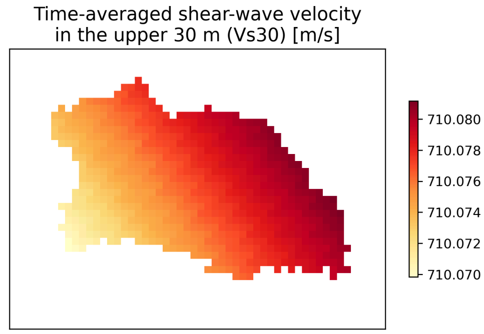
Calculation:
(3) Calculate Average Flow Type score
$Flow\ Type = (3 + 2 + 1 + 3) / 4 = 2.25$
Suitable flow type: Hyperconcentrated
Corresponding bulking factor range interval: [1.25, 1.67]

Step 4. Refine the Bulking Factor Estimation

In step 4 we use five more variables to identify a refined bulking factor from the range identified in Step 3. Five variables are used in this step: 1. Post Fire Debris Flow Likelihood, 2. Burn Probability, 3. Potential Fire Severity, 4. Shear wave Velocity of 30m (Vs30), and 5. Presence of loose sediment deposits. The first four variables are based on spatial datasets and are created automatically for the study site by the program. The final variable, presence of loose sediment, requires the user to assess for themselves and provide a manual entry of the result. You can see the data created and used in this step in Table 9.

Table 9. Variables used in Step 4 for Murphy Creek and a visualization of the datasets produced by the program

#	Variable	Visualization
3.2.7	PFDFL	
3.2.8	Burn probability	
3.2.9	Potential fire severity	

3.2.10	Vs30m shear wave velocity	
3.2.11	Presence of loose sediment deposits	Manual

The assessment of each variable can be seen in Table 10. In this step, each variable can be given an adjustment factor to scale their importance. This adjustment factor serves as a way to scale the variable according to engineering judgment. This provides an opportunity for engineering judgment to be used. For this scenario we are using equal adjustment factors for each variable. The post-fire debris flow likelihood for this basin is 60.63%, falling within the high risk category, with a score of 3. The burn probability variable is 1.70%, falling within the low risk category, with a score of 1. The potential fire severity variable is 21.52%, falling within the low risk category, with a score of 1. The shear wave velocity variable is 710.08m/s, falling within the low risk category, with a score of 1. The presence of loose sediment deposits variable is a manual entry, our assessment found no loose sediment deposits in the basin, meaning this variable was skipped in the calculation.

Table 10. Results of the Step 4 Murphy Creek Culvert Variable Assessment

#	Variable	Adjustment Factor	Low (+1)	Moderate (+2)	High (+3)	Results
3.2.7	Post-fire debris flow probability (P)	1	P < 40%	40% ≤ P < 60%	P > 60%	60.63%
3.2.8	Burn probability	1	< 5%	5 % < P < 10%	> 10%	1.70%
3.2.9	Potential fire severity	1	< 25%	25% < P < 50%	> 75%	21.52%
3.2.10	Vs30m shear wave velocity	1	>500 m/s	250-500m/s	<250 m/s	710.08 m/s
3.2.11	Presence of Loose Sediment deposits in basin	1	-	-	Yes	None

Next, we calculate the percentile as shown below, resulting in a percentile of 0.5.

Calculation:
(2) Calculate percentile (p) using β scores for each variable:

$$p = ((1 \times 3) + (1 \times 1) + (1 \times 1) + (1 \times 1)) / (4 \times 3) = 0.5$$

Step 5. Calculate Bulking Factor

In the final step, we calculate the refined bulking factor using the percentile from step 4 to identify what value from the bulking factor range should be used. In step 3 we identified the probable flow type to be hyperconcentrated, with a given Q100 BF range of 1.25-1.67. For Murphy Creek culvert we get a bulking factor of 1.46. The calculation can be seen below.

Calculation:
(3) Calculate BF:

$$BF = 1.25 + (1.67 - 1.25) \times 0.5 = 1.46$$

Final bulking factor estimate = 1.46
Total elapsed time = 122.3 seconds (2.04 minutes)

4.2.1 Impact of Engineering Judgment: Adjusting the Weights for Murphy Creek

We can adjust the relative weight of each variable in Step 4 based on engineering judgment around the risk that variable represents for our site. For instance, if we see that in general PFDFL overpredicts for northern California, we may want to reduce the level of risk this variable shows by giving it an adjustment factor less than 1. But, the sum of all adjustment factors must equal the total number of variables used. So, if we lower the PFDFL adjustment factor to 0.8, we need to increase other adjustment factors by 0.2. In this case, we know that Vs30 is an important variable for rock strength, and so we can increase the risk that Vs30 variable shows by changing its adjustment factor to 1.2. This would lead to a percentile of 0.466, and a slightly lower bulking factor than if we did not change the adjustment factors.

Table 11. Results of the Step 4 Murphy Creek Culvert Variable Assessment

#	Variable	Adjustment Factor	Low (+1)	Moderate (+2)	High (+3)	Results
3.2.7	Post-fire debris flow likelihood (P)	0.8	P < 40%	40% ≤ P < 60%	P > 60%	60.63%
3.2.8	Burn probability	1	< 5%	5 % < P < 10%	> 10%	1.70%
3.2.9	Potential fire severity	1	< 25%	25% < P < 50%	> 75%	21.52%
3.2.10	Vs30m shear wave velocity	1.2	>500 m/s	250-500m/s	<250 m/s	710.08 m/s
3.2.11	Presence of Loose Sediment deposits in basin		-	-	Yes	None

Calculation:
(2) Calculate percentile (p) using β scores for each variable:

$$p = ((0.8 \times 3) + (1 \times 1) + (1 \times 1) + (1.2 \times 1)) / (4 \times 3) = 0.466$$

4.3 Assessing Big Creek, Hwy 1

The area of the contributing basin for Big Creek bridge is over 57km^2. Using the thresholds derived from the literature and discussed with the TAC, such a basin would be expected to produce only normal fluvial flows. And due to the large basin area, this case study is probable to have a long watershed length, and low Melton ratio, indicating a low likelihood of a sediment-laden flow. Yet we know that following the Dolan Fire (August 2020), an intense winter rain (Jan 2021) produced a debris flood that passed under the Hwy 1 bridge, leaving a 2-3m thick deposit of stratified sand and gravel, characteristic of debris floods. We were able to observe this deposit after conducting a field visit to the site. Looking into why the method does not predict such an event sheds light on the limitation of the widely-used morphology criterion for predicting debris flows likelihood.

During the January 2021 storm, debris flows initiated in the downstream-most tributaries above the bridge: Cathedral Creek, which drains about 2km^2 and whose confluence with Big Creek is about 2.9 km upstream of the Hwy 1 bridge, and Brunette Creek, which drains about 2.6km^2 and which joins mainstem Big Creek about 1.6 km upstream of the bridge (Figure 10). In this case, debris flows were generated on small, steep tributary basins, and the sediment flowed downstream as a debris flood to reach the bridge. As of summer 2021, there were 2-3-m thick deposits of mostly stratified sediments flanking the lower 2 km of Big Creek, classic debris-flood deposits (Dodd, 2021; DeWit et al., 2022; Olsen, 2023).

As illustrated by our case study application, neither our method – nor relations published by other researchers relating drainage area to debris flow occurrence – predict a sediment laden flow at the bridge. The Big Creek experience highlights the importance of engineering judgment when determining flow type and the final bulking factor. It further highlights the importance of looking into the history of any documented past sediment-laden flows, as important background information for the district engineer's evaluation. With this history in mind, we can run through the Big Creek case study.

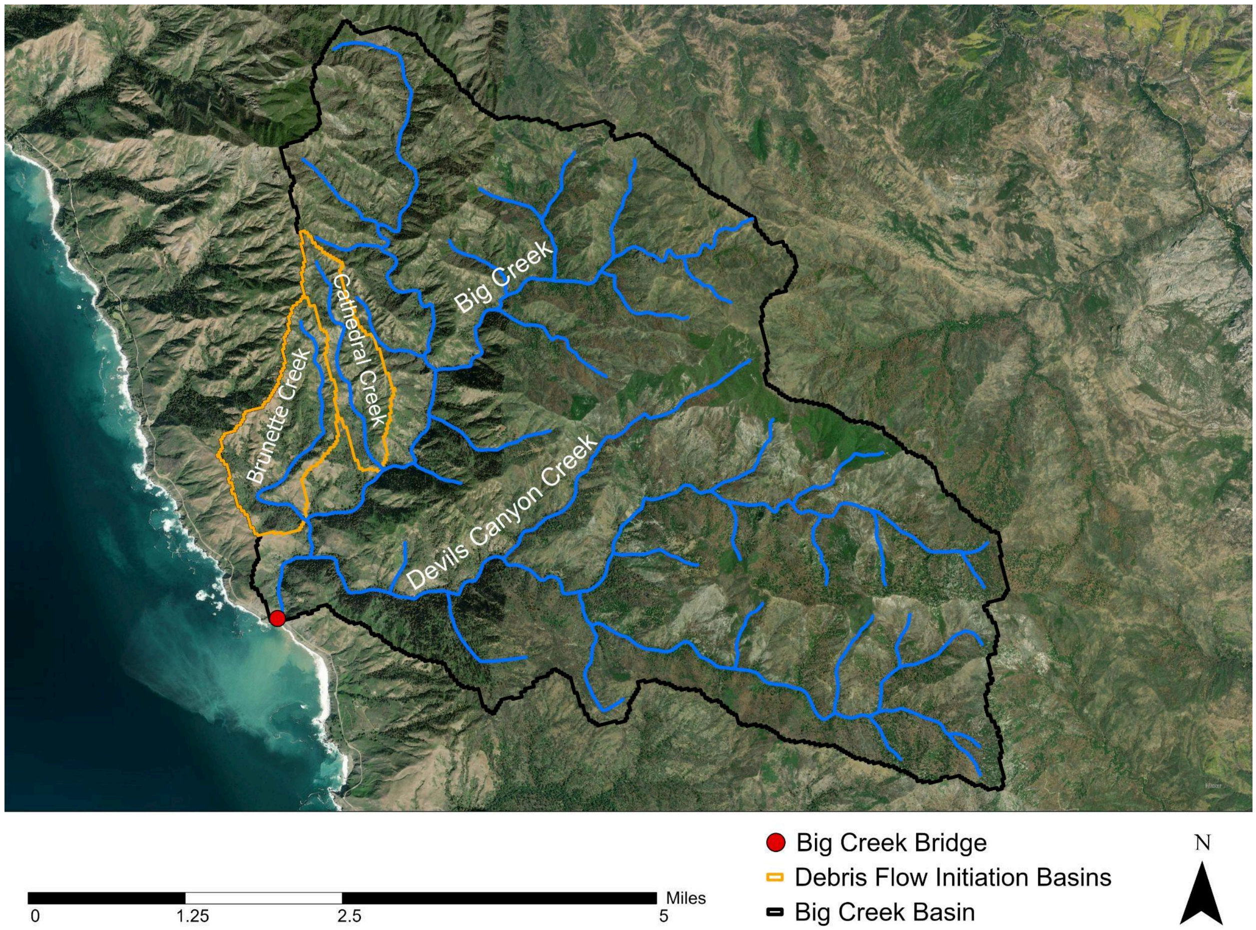


Figure 10. Big Creek Bridge Contributing Basin and the Basins in which debris flows were initiated.

Step 1. Identify Asset's Coordinates

Step one is to identify the asset's coordinates. The Big Creek crossing is located at 21°35'57.2"W, 36°04'13.1"N as seen in Figure 11. The post-fire flood brought debris from the recently burned basin, but this bridge is 65 ft high and over 500 ft long, so it was not impacted by the debris flow and flood.

Figure 11. Big Creek Bridge

Step 2. Delineate Contributing Basin and Basin Characteristics

Step two is delineating the contributing basin, and gathering the data that describe the basin characteristics. In this step we generate the base GIS datasets needed to compute the variables required for expected flow type estimation and bulking factor refinement in Steps 3, 4, and 5. First, we extract the contributing basin using the StreamStats API and compute basin characteristics and flow statistics (Figure 12). Then, we compute the DEM and slope datasets from the 3DEP API (Figure 13). We have the option of downloading these datasets and opening them in ArcPro ourselves, or running the analysis through the program provided. Once we know the contributing basin and have its shapefile, we can download all the data necessary for our basin that will be used in the following steps.

Note that following the convention of other studies and our proposed method, we do not calculate debris flow probability separately for each small subwatershed, only for the aggregate drainage area draining to the bridge crossing. But as we know the debris flows in Cathedral and Brunette Creeks were able to run-out downstream as far as the Hwy 1 bridge, we can see that the actual physical process is not well represented by the calculations conducted over the entire $57km^2$ basin.

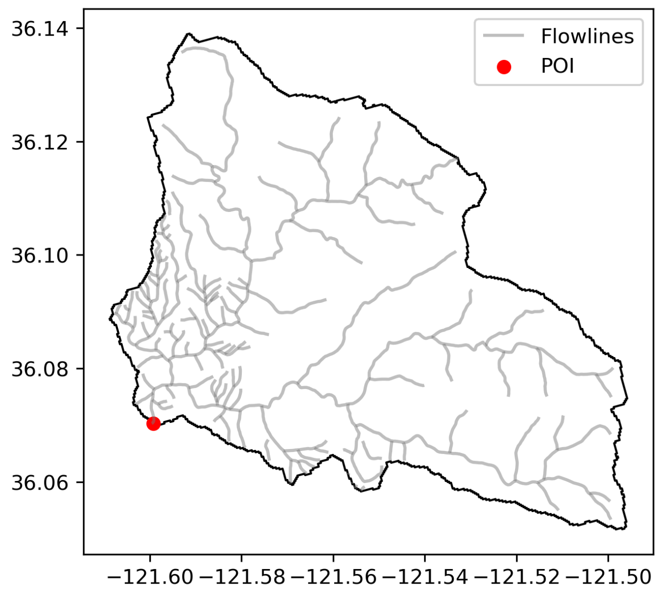


Figure 12. Basin and flowline characteristics calculated using the StreamStats API

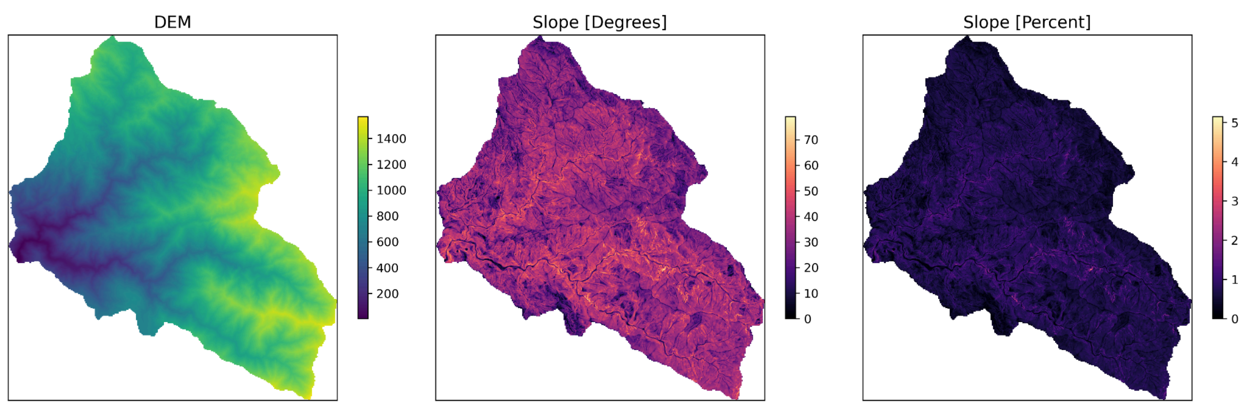
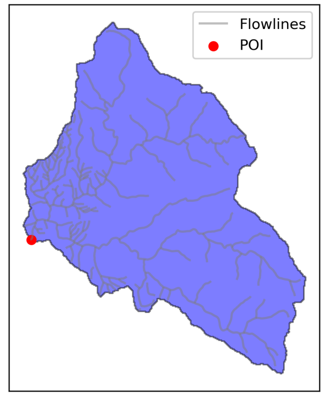
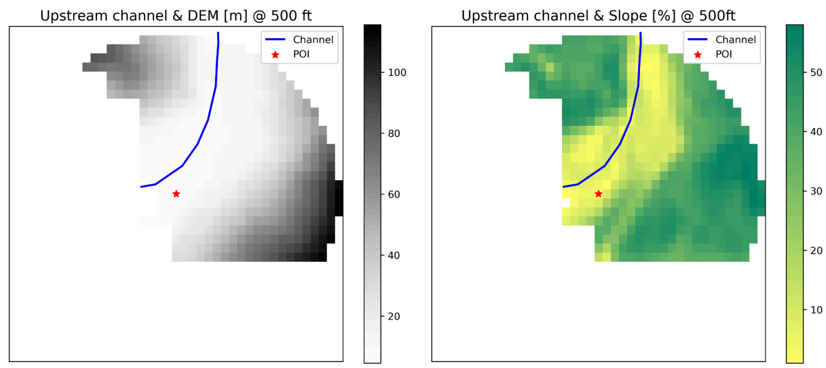
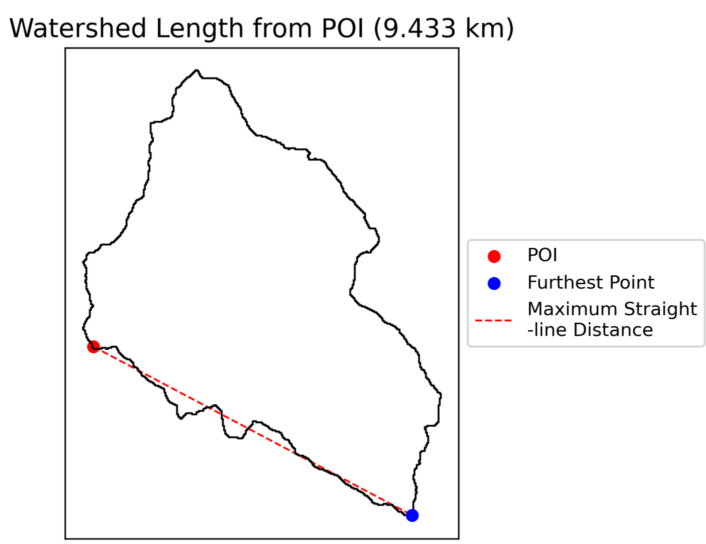


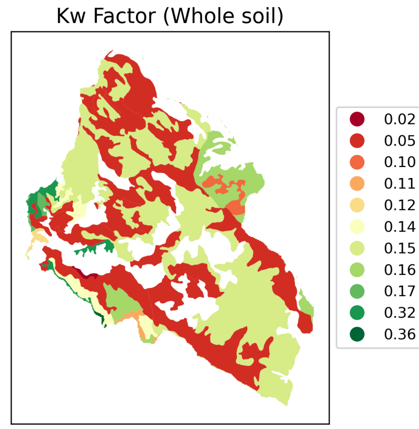
Figure 13. Topographic data clipped to the contributing basin

Step 3. Identifying flow type and corresponding bulking factor ranges

In Step 3 we identify the probable peak flow type for the Big Creek crossing. We gather the data for each of the six variables used to determine probable flow type: 1. Basin area, 2. Channel slope, 3. Melton ratio and watershed length, 4. Erodibility Kw factor, 5. Alluvial Fan, and 6. History of sediment laden flow. Spatial data is used to assess the first four variables, but the last two variables: the presence of an alluvial fan and history of sediment laden flow, is determined by the user and requires a manual entry. When using the program we developed, the spatial data is automatically created and downloaded to your computer as can be seen in Table 12.

Table 12. Variables used in Step 3 for Big Creek Bridge and a visualization of the datasets produced by the program

#	Variable	Visualization
3.2.1	Basin area	
3.2.2	Channel slope	
3.2.3	Melton ratio and watershed length	

3.2.4	Kw Factor	
3.2.5	Alluvial fan	Manual
3.2.6	History of sediment deposits	Manual

An assessment of these variables can be seen in Table 13. The basin area is 57 km^2 , which falls within the threshold for a normal flow, with a score of 1. The Channel slope is 21.00%, which falls within the threshold of any flow type possible, meaning this variable is not considered. The melton ratio is 0.21 and the watershed length is 9.43km, which falls within the threshold for a normal flow, with a score of 1. Kw factor is 0.12, which falls within the threshold of normal flow, with a score of 1. The variables 'presence of an alluvial fan' and 'history of sediment laden flow' were unknown, leading to them not being considered. (Big Creek passes in a confined canyon all the way to its mouth, thus there would be no open valley bottom providing an opportunity for the creek to develop an alluvial fan.) In total, 3 of the 6 variables were used in this case.

Table 13. Results of the Step 3 Big Creek Bridge Variable Assessment

#	Flow Type	Any Flow Type Possible	Normal Flow	Hyperconcent-rated Flow	Debris Flow	Results
	Bulking Factor Range (E.g., HDM)	**-**	**0 - 1.25**	**1.25 - 1.67**	**1.67 - 2.00**	
	Score for Normalized Sum Calculation	**-**	**+1**	**+2**	**+3**	
3.2.1	Basin area	-	>23km^2	8 - 23km^2	0.02 - 8km^2	57.52km^2
3.2.2	Channel Slope (500ft upstream of asset)	≥3%	<3%	-		21.00%

3.2.3	Melton Ratio & Watershed length	-	Melton <0.3	Melton 0.3-0.6; or >0.6 with watershed length >1.677 mi	Melton >0.6 with watershed length <1.677 miles	0.21 & 9.43 km
3.2.4	Kw Factor	-	≤0.20	>0.2;≤0.4	>0.4	0.12
3.2.5	Alluvial fan	None	-	Upstream / on		None
3.2.6	History of Sediment laden flow	Unknown/None	-	Yes		None

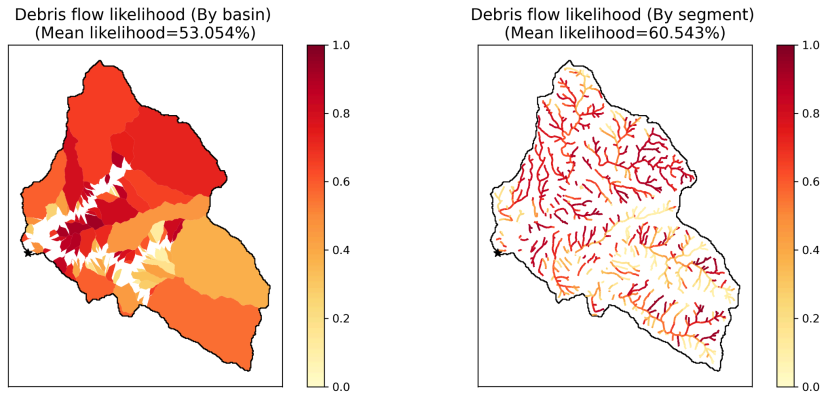
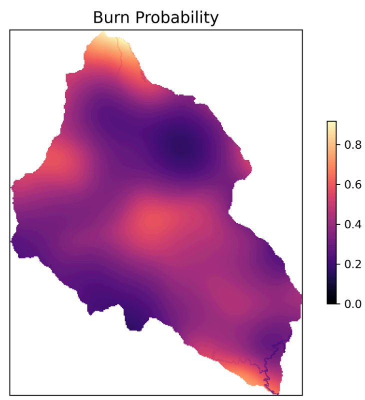
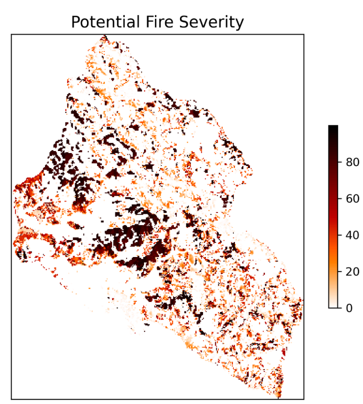
The average of these scores is then calculated to identify the flow type and corresponding bulking factor range interval. The average score for this site is 1, which directs us to expect a normal flow. In this assessment we are considering a Q100 event, and use a bulking factor range of 0-1.25 for normal flows. The calculations for this can be seen below. When using the program we developed, these calculations will be done automatically once all the variables are set, but the calculation can be done manually as well if preferred by the district engineer.

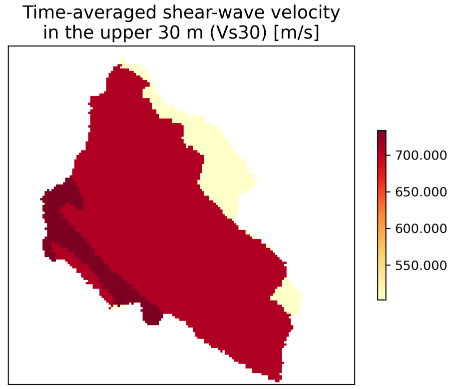
Calculation:
(3) Calculate Average Flow Type score
$Flow\,Type = (1 + 1 + 1)\,/\,3 = 1$
Suitable flow type: Normal
Corresponding bulking factor range interval: [0, 1.25]

Step 4. Refine the Bulking Factor Estimation
In step 4 we use five more variables to identify a refined bulking factor from the range identified in Step 3. Five variables are used in this step: 1. Post Fire Debris Flow Likelihood, 2. Burn Probability, 3. Potential Fire Severity, 4. Shear wave Velocity of 30m (Vs30), and 5. Presence of loose sediment deposits. The first four variables are based on spatial datasets and are created automatically for the study site by the program. The final variable, presence of loose sediment, requires the user to assess for themselves and provide a manual entry of the result. You can see the data created and used in this step in Table 14.

Table 14. Variables used in Step 4 for Big Creek and a visualization of the datasets produced by the program

#	Variable	Visualization

3.2.7	PFDFL	
3.2.8	Burn probability	
3.2.9	Potential fire severity	

3.2.10	Vs30m shear wave velocity	
3.2.11	Presence of loose sediment deposits	Manual

The assessment of each variable can be seen in Table 15. In this step, each variable can be given an adjustment factor, or weight, to scale their relative importance. This provides an opportunity for engineering judgment to be used. For this scenario we are using equal weighting for each variable, meaning we do not want to adjust the scores of these variables. The post-fire debris flow likelihood for this basin is 53.05%, falling within the moderate risk category, with a score of 2. The burn probability variable is 0.38%, falling within the low risk category, with a score of 1. The potential fire severity variable is 14.19%, falling within the low risk category, with a score of 1. The shear wave velocity variable is 686.53m/s, falling within the low risk category, with a score of 1. The presence of loose sediment deposits variable is a manual entry, our assessment found no loose sediment deposits in the basin, meaning this variable was skipped.

Table 15. Results of the Step 4 Big Creek Bridge Variable Assessment

#	Variable	Adjustment Factor	Low (+1)	Moderate (+2)	High (+3)	Results
3.2.7	Post-fire debris flow probability (P)	1	P < 40%	40% ≤ P < 60%	P > 60%	53.05%
3.2.8	Burn probability	1	< 5%	5 % < P < 10%	> 10%	0.38%
3.2.9	Potential fire severity	1	< 25%	25% < P < 50%	> 75%	14.19%
3.2.10	Vs30m shear wave velocity	1	>500 m/s	250-500m/s	<250 m/s	686.53 m/s
3.2.11	Presence of Loose Sediment deposits in basin	1	-	-	Yes	None

Next, we calculate the percentile using the calculation shown below, resulting in a percentile of 0.417.

Calculation:
(2) Calculate percentile (p) using β scores for each variable:

$$p = ((1 \times 2) + (1 \times 1) + (1 \times 1) + (1 \times 1)) / (4 \times 3) = 0.417$$

Step 5. Calculate Bulking Factor
In the final step, we calculate the refined bulking factor using the percentile from step 4 to identify what value from the bulking factor range should be used. In step 3 we identified the probable flow type to be normal flow, with a given Q100 BF range of 0-1.25. For the Big Creek crossing we get a bulking factor of 0.521. The calculation can be seen below.

Calculation:
(3) Calculate BF:

$$BF = 0 + (1.25 - 0) \times 0.417 = 0.521$$

Final bulking factor estimate = 0.521
Total elapsed time = 211.8 seconds (3.53 minutes)

4.3.1 Impact of Engineering Judgment: Adjusting the Basin for Big Creek

In order to address the possible problem of sediment-laden flow potential being hidden by the geometries of a large watershed, when working within a large watershed district engineers have the option of running the method again on smaller basins within their project's contributing basin. We provide an example of this using the Big Creek Bridge case study as an example. We made a sub-basin within the Big Creek bridge watershed for Brunette and Cathedral Creeks (Figure 14). Using this sub-basin, we re-ran the case study to see what the results would be considering just these nearest tributaries along Big Creek.

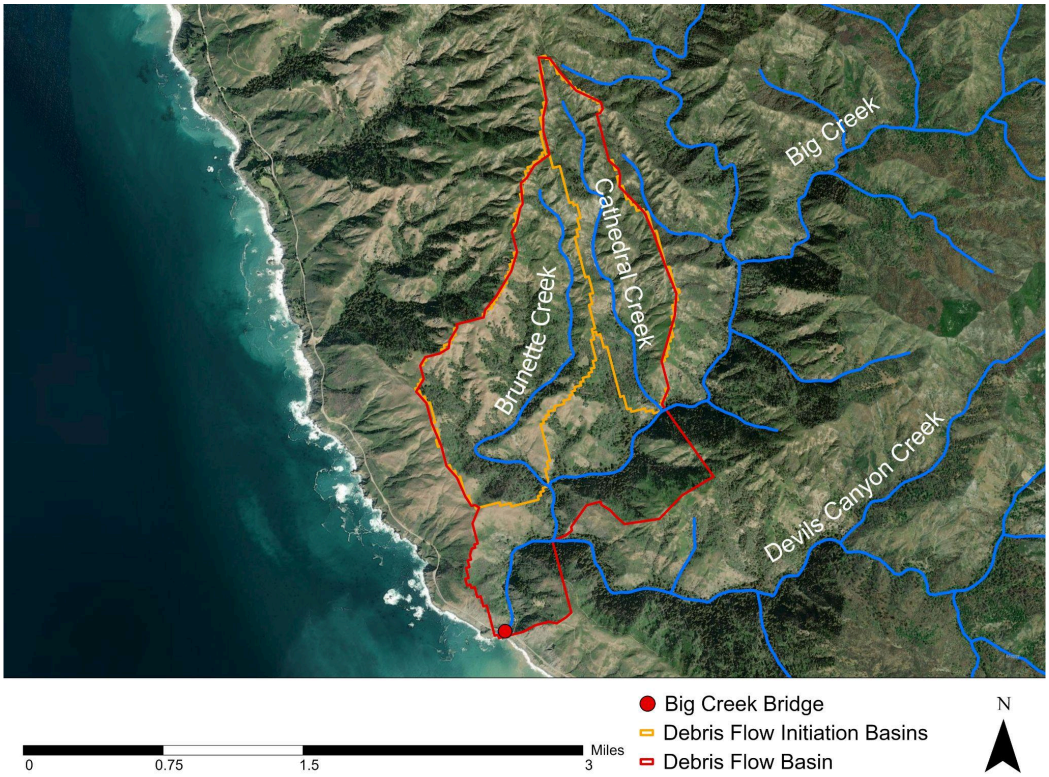


Figure 14. Sub-basin for tributaries of Big Creek created for further assessment.

Step 2. Delineate Contributing Basin and Basin Characteristics

Step 1 was the same, but in Step 2, we created the new sub-basin in ArcPro using the basins created in StreamStats for Brunette Creek, Cathedral Creek, and Big Creek tributary to create the outline. Then we used our manually created basin shapefile in the program to calculate the watershed geometries and download all needed datasets. The sub-basin shapefile and its flowlines can be seen in Figure 15.

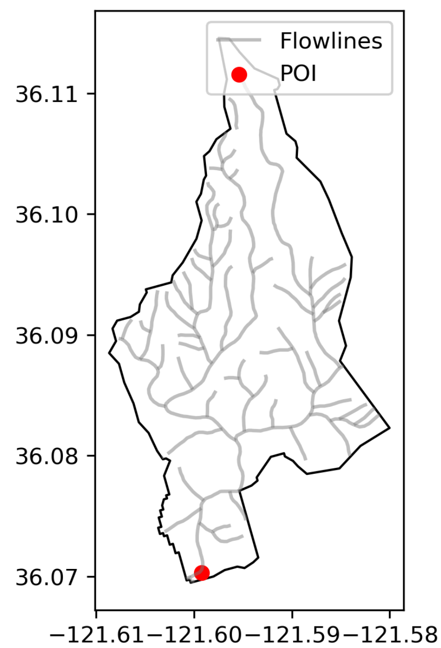


Figure 15. Manually created Basin along with the flowline characteristics calculated using the StreamStats API

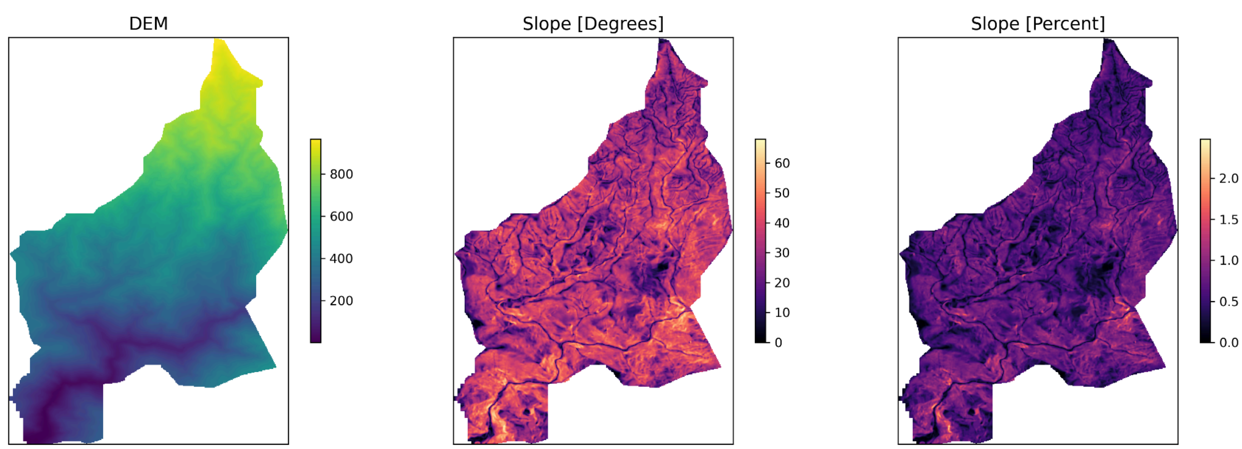


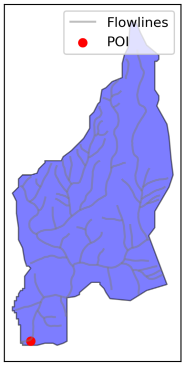
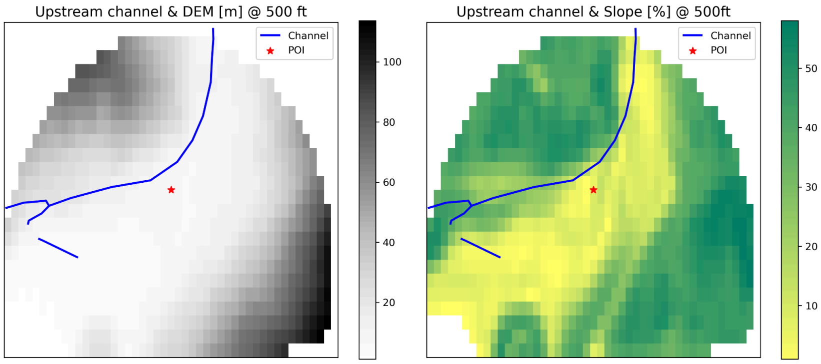
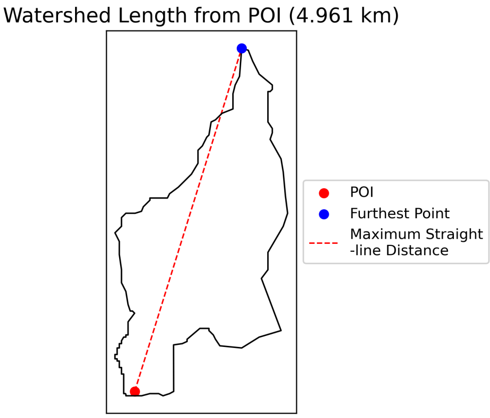
Figure 16. Topographic data clipped to the contributing basin

Step 3. Identifying flow type and corresponding bulking factor ranges

The new variable visualizations can be seen in Table 16. The results of the analysis can be seen in Table 17. The sub-basin area is 6.143km^2 , which falls within the threshold for a debris flow, with a score of 3. The Channel slope is 45.05%, which falls within the threshold of any flow type possible, meaning this variable is not considered. The melton ratio is 0.389 and the watershed length is 4.961km, which falls within the threshold for a hyperconcentrated flow, with a score of 2. Kw factor is 0.14, which falls within the threshold of normal flow, with a score of 1.

The variables ‘presence of an alluvial fan’ and ‘history of sediment laden flow’ were unknown, leading to them not being considered (Big Creek passes in a confined canyon all the way to its mouth, thus there would be no open valley bottom providing an opportunity for the creek to develop an alluvial fan). In total, 3 of the 6 variables were used in this case.

Table 16. Variables used in Step 3 for Big Creek Bridge Sub-Basin and a visualization of the datasets produced by the program

#	Variable	Visualization
3.2.1	Basin area	
3.2.2	Channel slope	
3.2.3	Melton ratio and watershed length	

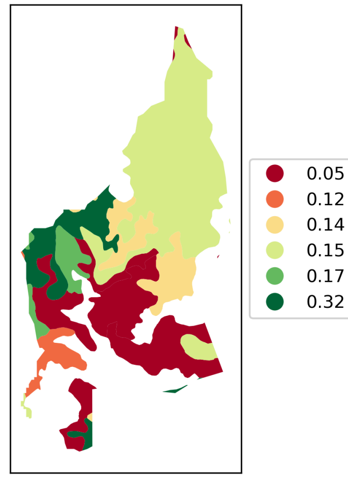
3.2.4	Kw Factor	Kw Factor (Whole soil) 
3.2.5	Alluvial fan	Manual
3.2.6	History of sediment deposits	Manual

Table 17. Results of the Step 3 Big Creek Bridge Sub-Basin Variable Assessment

#	Flow Type	Any Flow Type Possible	Normal Flow	Hyperconcent -rated Flow	Debris Flow	Results
	Bulking Factor Range (E.g., HDM)	**-**	**0 - 1.25**	**1.25 - 1.67**	**1.67 - 2.00**	
	Score for Normalized Sum Calculation	**-**	**+1**	**+2**	**+3**	
3.2.1	Basin area	-	>23km^2	8 - 23km^2	0.02 - 8km^2	6.143km^2
3.2.2	Channel Slope (500ft upstream of asset)	≥3%	<3%	-		45.05%
3.2.3	Melton Ratio & Watershed length	-	Melton <0.3	Melton 0.3-0.6; or >0.6 with watershed length >1.677 mi	Melton >0.6 with watershed length <1.677 miles	0.389 & 4.961 km
3.2.4	Kw Factor	-	≤0.20	>0.2;≤0.4	>0.4	0.14

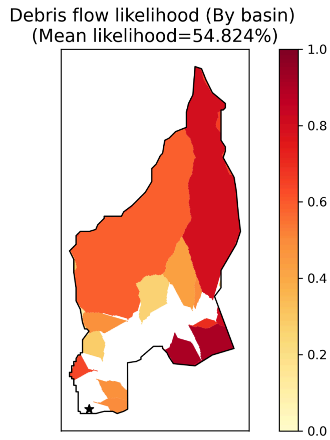
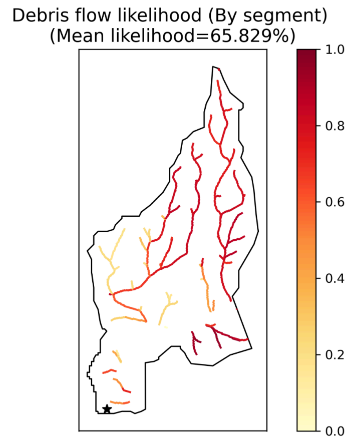
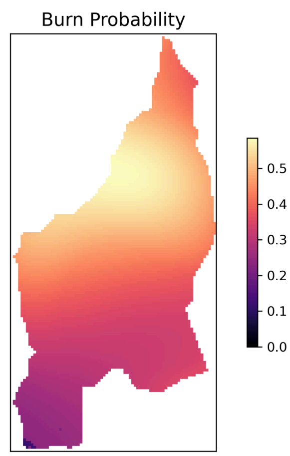
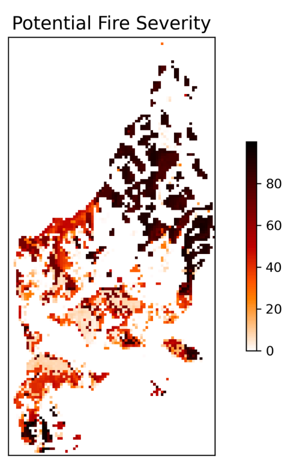
3.2.5	Alluvial fan	None	-	Upstream / on	None
3.2.6	History of Sediment laden flow	Unknown/None	-	Yes	None

The average of these scores is then calculated to identify the flow type and corresponding bulking factor range interval. The average score for this site is 2, which directs us to expect a hyperconcentrated flow. In this assessment we are considering a Q100 event, and use a bulking factor range of 1.25-1.67 for hyperconcentrated flows. The calculations for this can be seen below. When using the program we developed, these calculations will be done automatically once all the variables are set, but the calculation can be done manually as well if preferred by the district engineer.

Calculation:
(3) Calculate Average Flow Type score
$Flow\ Type = (3 + 2 + 1) / 3 = 2$
Suitable flow type: Hyperconcentrated
Corresponding bulking factor range interval: [1.25, 1.67]

Step 4. Refine the Bulking Factor Estimation
The visualization of the sub-basin datasets for step 4 can be seen in Table 18. The assessment of each variable can be seen in Table 19. For this scenario we are again using equal weighting for each variable. The post-fire debris flow likelihood for this basin is 54.82%, falling within the moderate risk category, with a score of 2. The burn probability variable is 0.41%, falling within the low risk category, with a score of 1. The potential fire severity variable is 22.17%, falling within the low risk category, with a score of 1. The shear wave velocity variable is 719.64m/s, falling within the low risk category, with a score of 1. The Presence of loose sediment deposits variable is a manual entry, our assessment found no loose sediment deposits in the basin, meaning this variable was skipped.

Table 18. Variables used in Step 4 for Big Creek sub-basin and a visualization of the datasets produced by the program

#	Variable	Visualization
3.2.7	PFDFL	 
3.2.8	Burn probability	
3.2.9	Potential fire severity	

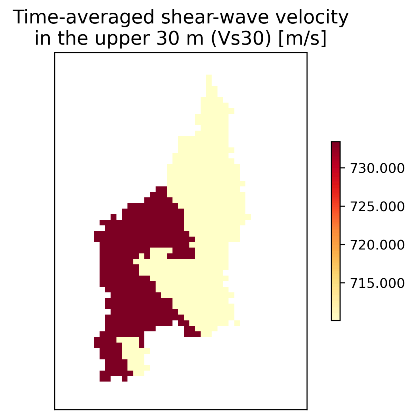
3.2.10	Vs30m shear wave velocity	
3.2.11	Presence of loose sediment deposits	Manual

Table 19. Results of the Step 4 Big Creek Bridge sub-basin Variable Assessment

#	Variable	Adjustment Factor	Low (+1)	Moderate (+2)	High (+3)	Results
3.2.7	Post-fire debris flow probability (P)	1	P < 40%	40% ≤ P < 60%	P > 60%	54.82%
3.2.8	Burn probability	1	< 5%	5 % < P < 10%	> 10%	0.41%
3.2.9	Potential fire severity	1	< 25%	25% < P < 50%	> 75%	22.17%
3.2.10	Vs30m shear wave velocity	1	>500 m/s	250-500m/s	<250 m/s	719.64 m/s
3.2.11	Presence of Loose Sediment deposits in basin	1	-	-	Yes	None

Next, we calculate the percentile using the calculation shown below. The percentile result was the same as for the entire basin, resulting in a percentile of 0.417.

Calculation:
(2) Calculate percentile (p) using β scores for each variable:

$$p = ((1 \times 2) + (1 \times 1) + (1 \times 1) + (1 \times 1)) / (4 \times 3) = 0.417$$

Step 5. Calculate Bulking Factor

In the final step, we calculate the refined bulking factor for the sub-basin using the percentile from step 4 to identify what value from the bulking factor range should be used. In step 3 we identified the probable flow type to be hyperconcentrated flow, with a given Q100 BF range of 1.25-1.67. For the Big Creek crossing sub-basin we get a bulking factor of 1.425. The calculation can be seen below.

Calculation:
(3) Calculate BF:

$$BF = 1.25 + (1.67 - 1.25) \times 0.417 = 1.425$$

Final bulking factor estimate = 1.425
Total elapsed time = 38.4 seconds

5. Conclusion

Post-fire flooding is a growing risk in California, with implications for urban settlements and transportation infrastructure. Southern California has a long history of wildfires and post-fire flash floods and debris flows, especially in the Transverse Ranges. To account for the increased volume of flow resulting from the sediment load added to floods by debris flows and debris floods (hyperconcentrated flows), public works agencies in southern California (Santa Barbara County and South) have developed sediment bulking factors with which to estimate how much larger they should design infrastructure to accommodate the larger flows draining burnt slopes (West Consultants, 2011). With the recent increase in wildfire throughout northern California, there is a recognized need for bulking factors that can be used in northern California as well.

While we anticipate that sediment bulking (and hydrologic response more generally) will be less extreme in northern California due to differences in relief, lithology, vegetative cover, and rainfall intensity, to date there is very few empirical data with which to develop relationships.

This project was intended to focus on sediment bulking only, and did not directly consider related factors such as increased clearwater runoff, and bulking from woody debris and trash.

After conducting a literature review (submitted Spring 2023), we investigated numerous variables correlated with sediment laden flow. From these we selected relevant variables that are publicly available in statewide GIS datasets. Building on the current bulking factor approach in the HDM, we developed a framework for assessing likely flow type and taking relevant information into account to estimate bulking factors. The framework can be applied manually, following the current approach detailed in the HDM. However, as much of this work can be tedious, we also developed an optional decision-support tool to aid bulking factor estimation in an automatic and flexible way. Use of this decision support tool is explained in our report, an appendix, and in a video going over the tool's use step by step. To illustrate application of the tool, we provide two detailed case studies in this report, and have completed four other case studies, whose release is pending review by CGS.

The framework proposed here is more comprehensive than the framework in the current HDM, but is very much in line with the spirit of the HDM approach in giving district engineers leeway in determining appropriate sediment bulking factors. As more data are compiled in future years following future fires, the approach can be improved by drawing upon more complete data sets, especially with respect to northern California conditions. We highlight that CGS is currently preparing a new, revamped model for debris flow likelihood, which should improve predictions of bulked runoff.

The decision support tool is widely applicable across the state, but should be regarded as only one source of information upon which the district engineer should make a determination of appropriate bulking factor for a given site. The calculated bulking factor is not purported to be the "true" value, but it supports an iterative process towards finding a suitable sediment bulking factor. We have used the best available data sets in our method, and provided code that automatically retrieves the relevant data for the drainage basin above a given asset (culvert, bridge).

Sediment bulking is limited by the physical processes of how much sediment a given flow of water can carry, such that sediment bulking cannot exceed 2 or 2.5. It is useful to keep in mind that post-fire runoff has been documented to be 10-30 times greater than pre-fire runoff, attributable to hydrologic effects such as reduced infiltration. Thus sediment bulking, the focus of our study, is only one factor in increasing post-fire runoff. Another important factor is the effect of large woody debris and trash in blocking culverts and bridge openings (which has been termed 'dynamic bulking'). Our approach does not address the effects of large wood or trash.

The case studies illustrate the application of the approach generally and the decision support tool. An important caveat with the case studies is that whether a debris flow occurs or not depends not only on the 'static' factors assessed in debris flow probability models (and the variables considered in our framework), but also the weather: whether an intense rain occurs soon after a severe burn. Thus, when reviewing case studies, we cannot use the occurrence (or non-occurrence) of a sediment-laden flow as a 'test' of the method, as the intensity of rain during the vulnerable post-fire period is a wildcard.

The Murphy Creek example illustrates use of the approach and the decision support tool. In this case study we also illustrate the potential for the district engineer to use professional judgment in determining bulking factor by adjusting weights given to different variables. For this example, we assume that a debris flow (or at least a debris flood) occurred here following the Dixie Fire in light of the appearance of the creek and the road crossing on aerial imagery. However, we were unable to visit the site so could not observe sedimentology and stratigraphy of the fan deposit, so cannot confirm the flow type with certainty. Nonetheless, the framework predicts a sediment-laden flow (debris flow or debris flood), and one occurred that was large enough to close the highway for some time.

The Big Creek example is perhaps most interesting for its cautionary note about using drainage area as a variable to determine flow type. While drainage area has frequently been used as a variable predicting the likelihood of a debris flow or flood, and larger drainage areas are assumed to be incapable of producing such flows, Big Creek illustrates how two small, steep tributaries that join mainstem Big Creek only 2.9 and 1.6 km above the creek mouth can 'load' the mainstem with sufficient sediment to produce a debris flood down to the Hwy 1 bridge. The case study also illustrates how running the decision support tool model with a redefined drainage area of only the lower basin (encompassing Cathedral and Brunette Creeks, and adjacent local drainage to Big Creek) could yield different predictions of sediment laden flow (and thus bulking factors).

It is hoped that this updated method can assist Caltrans district engineers in quickly gathering data and assessing variables that inform the risk of sedimentation in possible post-fire flooding to logically identify an estimated sediment bulking factor.

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