# FLOOD AFTER FIRE
# CALIFORNIA TOOLKIT

A RESOURCE FOR TECHNICAL SPECIALISTS
TO ASSESS FLOOD AND DEBRIS FLOW RISK
AFTER A WILDFIRE

September 2020

Version 1

*Cover Photos courtesy of Ventura County:*

*CENTER:*

*Flooded road*

*OUTSIDE, CLOCKWISE:*

*Bird's eye view of the Thomas Fire*

*A culvert plugged by debris*

*A car lifted by a debris flow*

*Large rocks deposited in a road*

*A gate holding back debris*

This Flood After Fire: California Toolkit is a collaborative, living document written by the California Silver Jackets Team. Silver Jackets is a partnership program that brings together Federal, State, local, and Tribal agencies to find collaborative solutions to complex flood risk management issues.

Agencies that contributed to this guide include:

Bureau of Land Management
California Department of Forestry and Fire Protection
California Department of Transportation
California Department of Water Resources
California Geological Survey
California Office of Emergency Services
County of Lake, California, Water Resources
Federal Emergency Management Agency
National Aeronautics and Space Administration
National Ocean and Atmospheric Administration
National Park Service
National Weather Service
Natural Resources Conservation Service
Santa Barbara County, California
U.S. Army Corps of Engineers, Engineer Research and Development Center
U.S. Army Corps of Engineers, Sacramento District
U.S. Forest Service
U.S. Geological Survey
Ventura County, California, Public Works Agency

## What is in This Toolkit?

- A collection of tools, methods, and other resources – grouped into chronologically distinct periods of a flood after fire response timeline – to help assess the risks associated with flooding and debris flow after a fire.
- Basic checklists and generalized procedures, written to encourage an interdisciplinary response to post-fire modeling and analysis.
- Appendices to help guide those who do not frequently respond to fire events. For more experienced emergency response officials or those who become familiar with this toolkit, the matrices provided can act as a "quick reference" to commonly used models and data.
- References and discussions on the roles different agencies of varying levels of government may have in response to wildfire.
- Technical resources that are useful for well-trained and experienced technical specialists, not the general public or communities impacted by wildfires and the floods and debris flows that could follow them. The information provided is specific to California.

## Who is This Toolkit For?

- GIS specialists, hydrologists, hydraulic engineers, or those with similar backgrounds.
- Geohazard specialists, geologists, mitigation planners, soil scientists, or other natural resource professionals may find this toolkit informative, but of limited use.
- Wildfire support staff such as Emergency Managers and those above who are responding to wildfires in the State of California.

## How is This Toolkit Used?

- This toolkit is designed to be used on a computer, and uses links to accompanying documents, files, and websites/data sources that are built into the text. However, a hardcopy can be printed and referenced if the user has ample and adequate access to data.
- For maximum benefit, this toolkit should be reviewed during the offseason (Chapter 2), or when there is not an emergency, so the reader becomes familiar with its structure and content. That said, this toolkit can be used during an emergency by relying heavily on the table of Contents and headings to take the reader to the most relevant sections.
- Those who do not frequently assess flood risk after a wildfire should follow the chapters and sections in order, beginning with Chapter 3 (Fire Event and Pre-Flood).
- Experienced emergency response officials or technical support staff can use the toolkit in the order they judge to be appropriate, based on what period of the fire response timeline they are in and what risk(s) they need to analyze and identify.
- Experienced modelers familiar with how interagency teams in California cooperate and respond to wildfires may find that the appendices are a useful "quick reference". In that case, much of the main text of the toolkit could be skipped, but used as a refresher.

# Table of Contents

## List of Tables



## List of Figures

# List of Acronyms and Abbreviations

ac ... Acre
AAR ... After Action Report (or Review)
ADH ... Adaptive Hydraulics Model
AGWA ... Automated Geospatial Watershed Assessment
AOI ... Area of Interest
BAER ... Burned Area Emergency Response
BARC ... Burned Area Reflectance Classification
BIA ... Bureau of Indian Affairs
BLM ... Bureau of Land Management
BMP ... Best Management Practice
CAL FIRE ... California Department of Forestry and Fire Protection
Cal OES ... California Governor's Office of Emergency Services
Caltrans ... California Department of Transportation
CGS ... California Geological Survey
CN ... Curve Number
DEM ... Digital Elevation Model
DHS ... Department of Homeland Security
dNBR ... differenced Normalized Burn Ratio
DOD ... Department of Defense
DOI ... Department of the Interior
DWR ... California Department of Water Resources
ERMiT ... Erosion Risk Management Tool
ESR ... Emergency Stabilization and Rehabilitation
FAF ... Flood After Fire
FEMA ... Federal Emergency Management Agency
FOUO ... For Official Use Only
FRAP ... Fire and Resource Assessment Program
GIS ... Geographic Information System
GISS ... GIS Specialist
H&H ... Hydrologic and Hydraulic
HEC ... Hydrologic Engineering Center, U.S. Army Corps of Engineers
HEC-GeoHMS ... Hydrologic Engineering Center-Geospatial Hydrologic Model System Extension
HEC-HMS ... Hydrologic Engineering Center-Hydrologic Modeling System
HIFLD ... Homeland Infrastructure Foundation-Level Data
HMS ... Hydrologic Modeling System
HUC ... Hydrologic Unit Code
ICP ... Incident Command Post
IFSAR ... Interferometric Synthetic Aperture Radar
JFO ... Joint Field Office
LiDAR ... Light Detection and Ranging

NBI ........ National Bridge Inventory
NHD........ USGS National Hydrography Dataset
NID........ National Inventory of Dams
NIFC........ National Interagency Fire Center
NLD ........ National Levee Database
NOAA........ National Oceanic and Atmospheric Administration
NPS........ National Park Service
NRCS........ Natural Resources Conservation Service
NWS ........ National Weather Service
RCS........ Rowe, Countryman, Storey
RI ........ Recurrence Interval
RWQCB ........ Regional Water Quality Control Board
SBS ........ Soil Burn Severity
SRA........ State Responsibility Area
TNM ........ The National Map
USACE........ United States Army Corps of Engineers
USDA ........ United States Department of Agriculture
USFS ........ United States Forest Service
USFWS ........ United States Fish and Wildlife Service
USGS........ United States Geological Survey
UTM ........ Universal Transverse Mercator
VAR ........ Values-at-Risk
WBD........ Watershed Boundary Dataset
WEPP........ Water Erosion Prediction Project
WERT........ Watershed Emergency Response Team
WUI ........ Wildland Urban Interface

# 1. Introduction

Across the globe, the risk of large wildfires continues to increase. In the United States, it is estimated that wildfire potential in the Mountain West could increase six-fold by mid-century (Figure 1; NOAA, 2015). In California, the length of fire season is estimated to have increased by 75 days across the Sierra Nevada (CAL FIRE, 2019a) and the threat of catastrophic fire is high in many of the highly-populated parts of the State (Figure 2). The intensity of wildfires is also increasing (Figure 2). For example, the 2018 Camp Fire in Northern California's Butte County – the deadliest fire in California history – was only active for 17 days, but killed 85 people, destroyed 18,804 structures, burned over 150,000 acres (CAL FIRE, 2019b), and cost an estimated $16.5 billion in firefighting costs and infrastructure (Pike, 2019).

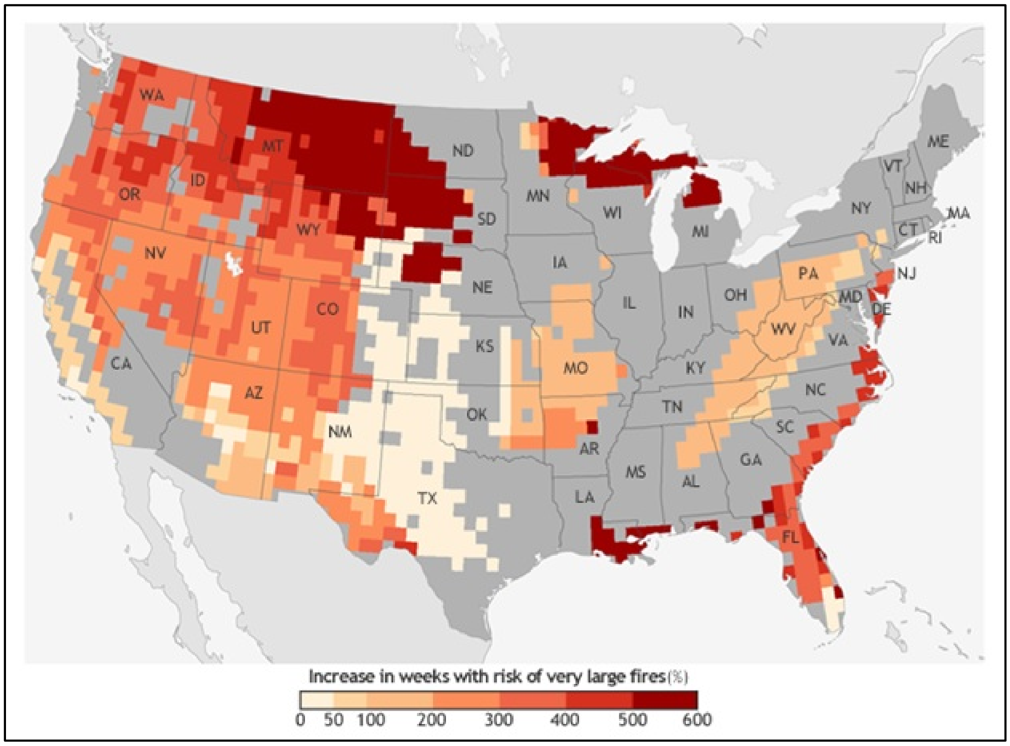


*Figure 1. Increase in Fire Risk by Mid-Century (NOAA, 2015).*

Extended droughts, increases in wildfire fuels, climate change, and expanding wildland-urban interfaces (WUI) are but a few contributors to global increases in wildfires and their destructiveness. Although wildfires are a disaster on the minds of many Californians, the well-known fire-flood sequence is sometimes overlooked, even though the risk of flooding after the fire remains for several years. Late autumn and winter wildfires further necessitate the need for pre-fire planning, including the development of tools and resources for geologic hazards and engineering evaluations. In California, these late season fires create a challenging situation for emergency managers as storms may impact a burned area while emergency response to wildfire is still in progress.

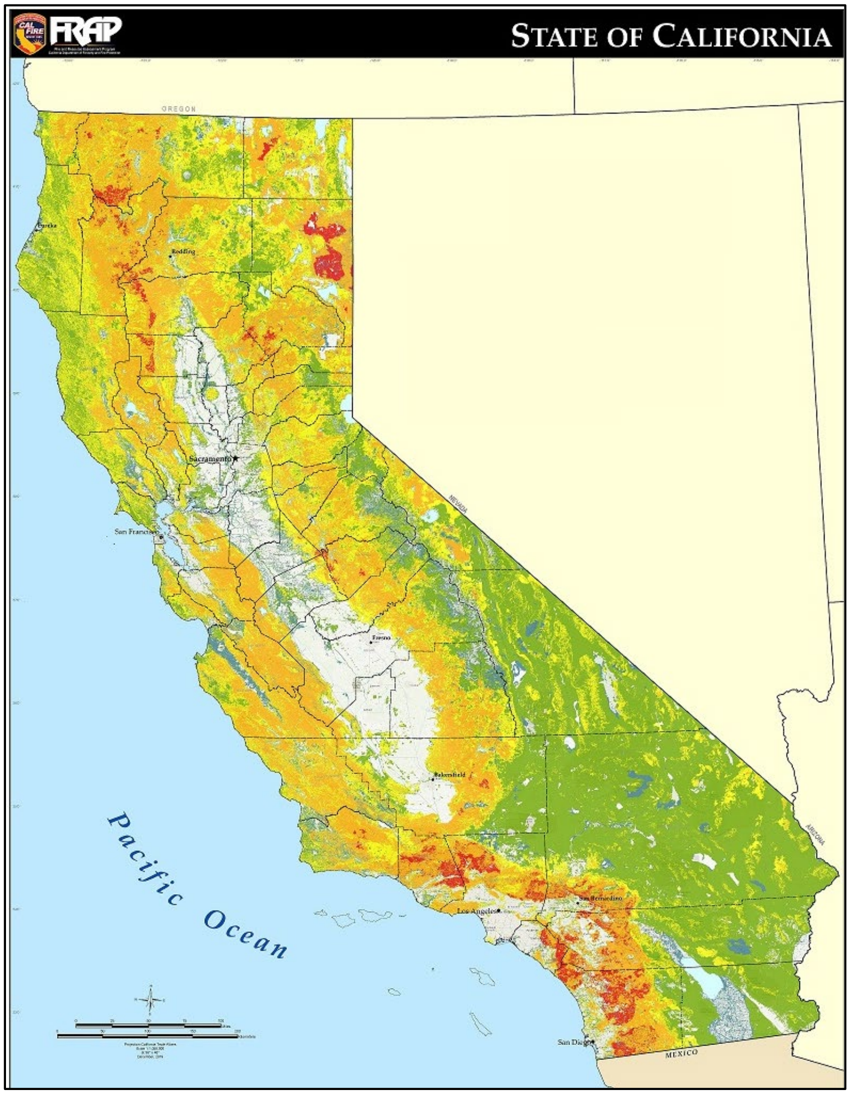


*Figure 2. California fire threat map. Colors represent wildfire risk. Red – extreme; orange – very high; yellow – high; green – moderate; blue – low; white – unmapped areas.*

The Thomas Fire dealt this challenge to Ventura and Santa Barbara counties. It started on December 4, 2017, and burned 281,893 acres, with full containment declared on January 12, 2018, after a storm and catastrophic debris flow event on January 9. As early as January 3, while the fire was still burning, the National Weather Service (NWS) communicated the potential for a strong storm in the coming week to the local emergency management and flood control partners (Laber, 2018). On January 6, the NWS issued a flash flood watch for the burn area given anticipated 1-hour rainfall rates of 0.5 to 1.0 inch/hour (12.7 to 25.4 mm/h) (Laber, 2018). At this time, an upper-level trough approached and deepened along the California coast and developed into a closed low-pressure system offshore of Point Conception. As the storm moved on shore the morning of January 9, intense rainfall passed through eastern Santa Barbara County and western Ventura County, triggering debris flows and sediment-laden flows on steep burned slopes within the Thomas Fire perimeter.

Debris flows issued from numerous watersheds within the Santa Ynez and Topatopa Mountains killed 23 people and caused severe damage to infrastructure, including 558 structures, 162 of which were considered destroyed (CAL FIRE, pers. comm.). Of the destroyed structures, 79 had complete structural damage including 41 structures that were swept off their foundations (Kean et al., 2019). Debris accumulated in low sections of Highway 101 (US 101), a major transportation corridor, rendering the section through Montecito impassable by vehicle for 13 days. Between January 9 and 22, first-responder personnel conducted search and rescue operations, provided life safety – and life sustaining – support. Before and during the event approximately 1,300 individuals were evacuated, and 700 sheltered-in-place (SBCOEM, 2018).

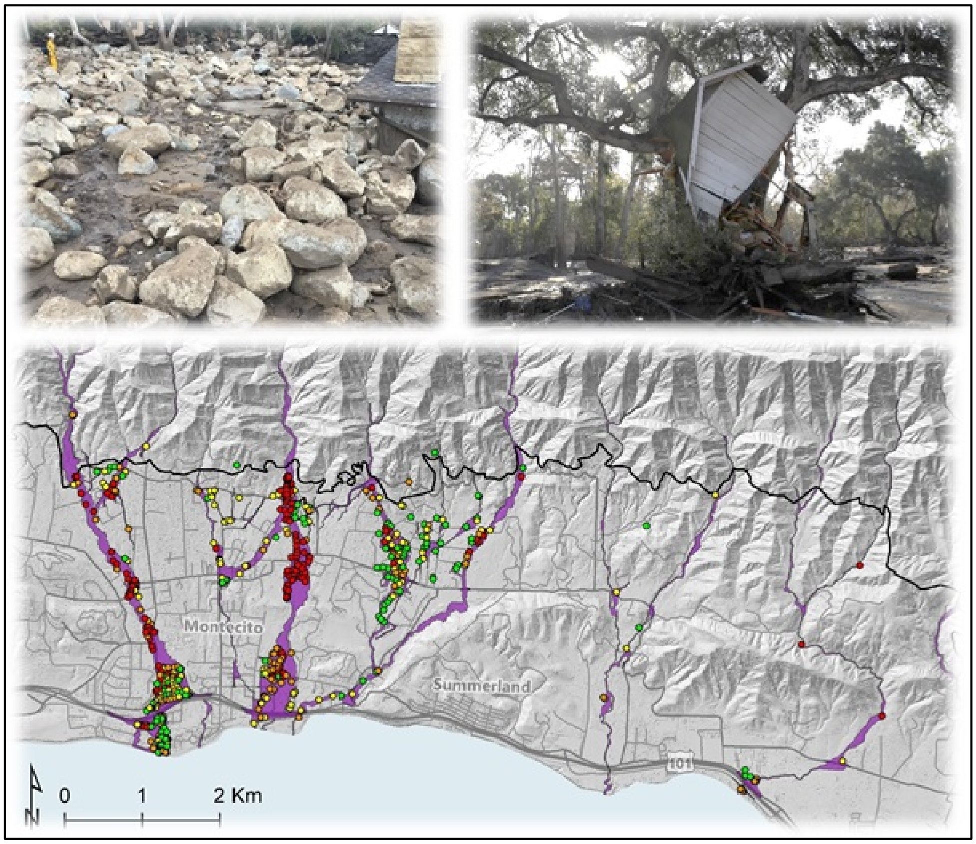


*Figure 3. Debris flows after the 2018 Thomas Fire (top left and top right); locations of structures damaged by debris flows (bottom half). Colors represent state of damage as identified by the CALFIRE-led damage assessment team. Green – slight; yellow – moderate; orange – high; red – destroyed. Map modified from Kean et al. (2019)*

This toolkit is one of the first attempts to provide a summary of the many technical principles and methodologies that are increasingly being used to prepare for flooding after a wildfire. These methods are becoming more common as professionals working in the Geographic Information Systems (GIS), engineering, geologic (geohazards), and hydrologic & hydraulic (H&H) engineering fields frequently join post-wildfire response teams. This document uses the term "flood" throughout to describe the full spectrum of post-wildfire flash flooding; from streamflows to hyper-concentrated flows to debris flows (Table 1).

Table 1. General classification of flow behavior (modified from Lancaster et al., 2015).

| **Flow Type** | **Sediment Load** | |
|---|---|---|
| | By Weight | By Volume |
| Streamflow | 1 – 40% | 0.4 – 20% |
| Hyperconcentrated flow | 40 – 70% | 20 – 60% |
| Debris flows | 70 – 90% | >60% |

The purpose of this toolkit is to act as a "playbook" that presents options to help select appropriate methods, models, or actions when working with a given set of data and/or circumstances after a wildfire. This toolkit is the culmination of decades of collective experience in wildfire response in California. It was written by a diverse group of experts from multiple government agencies across all levels of government; their experience in fields of geology, GIS, hydrology, hydraulics, engineering, soil science, flood risk management, and emergency response guided the primary subjects of this toolkit.

## What is in This Toolkit?

This toolkit contains a collection of tools, methods, and other resources that can be used when assessing the risks associated with flooding after a wildfire event in California. While it does provide some references and discussion on the roles different government agencies may have, it is not a replacement of those agencies' programs or emergency response procedures. This toolkit is targeted to data management, scientific, and engineering professionals, rather than the general public or individual members of communities impacted by wildfires and resulting floods. The information provided is targeted to the Western United States, but it uses details and examples that are specific to California.

The toolkit is organized into three generally recognizable periods: Fire Offseason, Fire Event/Pre-Flood, and Post-Flood Event (Flood-After-Fire). This can help a user of this toolkit more easily locate what portions of the toolkit they should review based on the period of time in which they are working. The toolkit also provides some checklists and generalized step-by-step procedures, and strives to integrate this information to encourage an interdisciplinary response to the risk of flood after fire. The toolkit can also be thought of as a "playbook" that provides multiple methods, tools, and resources that could be used to address flooding after fire.

What this toolkit does not provide is a comprehensive one-size-fits-all guide for responding to wildfires or addressing the risk of floods after a wildfire. All wildfires exhibit unique characteristics that contribute to the risk of flooding. The need for post-fire flooding and debris flow assessment will vary greatly, depending on the fire event's magnitude, location relative to population and infrastructure impacts, topography, soil burn severity, etc. Not all wildfires will need post-fire assessment for flood risk or flood flows, so users of this toolkit must approach each wildfire with flexibility. In that regard, this toolkit does not recommend, or intend to supersede, policies or prescribed actions for communities or agencies to undertake. Likewise, this toolkit does not recommend a particular software or methodology. It does provide some discussion on software, methods, tools, and other resources in the context of the information this toolkit's user has on hand.

## Who is This Toolkit For?

Because this toolkit is focused on the flood-after-fire threat, it is not directed at those responding to the fire event itself. It is also not designed as a guide for the general public. The key audience for this toolkit includes emergency managers, geohazard specialists, soil scientists, GIS specialists (GISS), and H&H engineers. The key audience also includes people with a background in the technical nature of working with spatial data, modeling flood risk and/or debris flows, or providing technical reports to emergency response officials. To that end, those who do not frequently respond to flood after fire events may find the appendices to be especially useful. The appendices provide methods, tools, and resources to use in a given set of circumstances. Experienced emergency response staff or officials may find that the appendices act as a quick reference that can support their efforts.

This toolkit focuses on assessing flash flood and debris flow risk after wildfires in California. This toolkit is appropriate for use in California's steep lands that frequently burn, have abundant sediment supply, and are situated upstream of populated areas at risk. Those who use it outside of California, or for other types of emergency response, may find that it does not suit their situation. However, if incorporated into a multi-hazard response plan, or as part of a larger disaster response effort, then this toolkit is likely to be helpful in supporting the appropriate response for potential post-fire flood events. Not all fires are equal – the response will ideally depend on the fire context. Fire location (proximity of affected communities), sheer size, fires with relatively steep terrain, and fires with a higher proportion of moderate and high burn severity are likely to trigger a higher level of post-fire flood and debris flow concern.

## 1.1. Fire Timeline and Response

Regardless of a community's level of fire preparedness, once the fire occurs, multiple agencies respond. They apply varying focus, tools, methodologies, and timelines of involvement to fulfill or perform their responsibilities and task objectives. Local government, usually via local law enforcement, may focus on residential evacuation while fire and utility crews are simultaneously arriving to fight the fire and repair critical infrastructure. Community needs will change from before the fire is contained, immediately after containment, and during the extended period following fire containment (see the After Wildfire Guide; Silver Jackets, 2019). All of this typically occurs before the risk of flood after the fire increases. As time and data collection progress, community response will also progress. Focus may change from egress and suppression to infrastructure protection, soil mass wasting mitigation, and preparation for possible flood and debris flow risk evaluation damages and response concerns.

This toolkit simplifies the multilevel, multi-agency timeline of activity and emergency response (see Appendix 6.1, the Resource Timeline Matrix) to flood-after-fire (FAF) into three time tiers. Each time tier is a generalized temporal snap shot of activities throughout a FAF response. Each time tier is distinguished by varying levels of data availability, agency responsibility, and timing. Figure 4 depicts a simple categorization of time tiers and stakeholder involvement.

Activities of stakeholders in each time tier are discussed throughout the document and outlined in greater detail in the Resource Timeline Matrix (Appendix 6.1). The Resource Timeline Matrix details stakeholder needs, methods, and tools. For example, post-fire flood and erosion analyses typically do not occur until a Burned Area Reflectance Classification (BARC) map is available sometime during Time Tier 1. A flood flow estimate made during pre-containment/immediate post-containment (Time Tier 1) may be optimized during Time Tier 2 to augment and produce higher fidelity flood risk prediction products and response management strategies. In general, most post-fire responses will move through these time tiers as part of the overall response. How post-fire response moves through these time tiers can be dependent on the fire event's magnitude and values at risks, the latter of which being somewhat dependent on the WUI. For example, a large fire in a remote area with no impact to population or infrastructure – meaning the WUI is small – may not proceed past Time Tier 1. In contrast, a smaller fire posing immediate risk or contributing to flood impacts to a densely populated area (i.e., large WUI) may go through all time tiers, possibly faster than the typically time periods shown in Figure 4.


*Figure 4. A generalized timeline of fire response*

# 2. Pre-Fire (Offseason)

The wildfire offseason refers to winter and spring seasons when large wildfires are typically unlikely events, conventionally December or January thru March or April. Over the last decade, the offseason has shortened in California, and in some years has been non-existent. Thus most but not all years have an offseason. Regardless of whether a fire occurs, the winter and spring are the fire training and preparedness season, particularly for Federal agencies. The term pre-season is also common, literal shorthand for preparedness-season. It has become crucially important for experts in both GIS and H&H disciplines to also prepare for the upcoming fire season. This means having data updated and organized, software licenses current, training reinforced, and new analytical techniques explored. New innovations in cartographic display and messaging should also be explored. And, of course, it means taking lessons learned from previous seasons and deployments, and integrating that knowledge as preparedness actions.

## 2.1. GIS Preparedness

GIS preparedness for an upcoming fire season is about being ready to react to a wildfire event on short notice. For a GISS, this may require an array of different strategies depending on the resources involved and the intended purpose or level of response. Regardless, preparedness is mostly about data: inventory, collection, and organization. Packaging the data library and copying it to a portable hard drive for deployments should be included as a necessary step (see Section 2.1.3 and Appendix 6.2, the Spatial Data Matrix). Other aspects of GIS preparedness include software updates, exploring new tools and analytical techniques, attending trainings, reviewing policy papers, and collaborating with colleagues through webinars or conferences. Offseason analysis and cartographic products may be prepared for situational awareness to agency management and the general public. This may include preparedness by Federal Burned Area Emergency Response (BAER) teams and state Watershed Emergency Response Teams (WERT) that will typically perform rapid (Time Tier 1) responses – necessitating thorough planning of GIS resources. The rapid responses are provided to agencies and private sector firms performing site-specific evaluations for mitigation engineering or broad-area evaluations with the purpose of long-term planning for mitigation and recovery. In these cases, the GIS data requirements may be similar, however, there are several distinctions depending on which phase of FAF response is being planned for. These include:

- Preparation of GIS data in the offseason
- Preparation of GIS data during the fire including field team applications using tablet-based software
- After the fire and pre-flood preparation including software needed to support geohazards and H&H specialists, including the incorporation of new spatial data such as LiDAR, aerial and satellite imagery

- After the fire and post-flood preparation including inundation mapping field team applications using tablet-based software, collection and incorporation of new field team data, new post-event spatial data such as LiDAR and imagery

Preparation of GIS data in the offseason may include the collection of spatial data for an area of intended operation. For example, at the Federal level there may be regions of operation that are logical boundaries for compiling data (e.g., National Forests - US Forest Service (USFS) Region 5, USACE South Pacific Division, or Federal Emergency Management Agency (FEMA) Region IX). At the State and local response level, logical boundaries might include CAL FIRE Units or Regions, counties, or groupings of counties. From this geographic basis spatial data may then be organized into different data type categories.

In addition to data organization, it is important that GIS professionals conduct regular offseason meetings with past deployment groups such as geologists, engineers, and other-agency GIS counterparts to gather feedback on what additional data and product refinements are recommended for future deployments. For example, if field applications are being used by field staff, it's important to share lessons learned and refine GIS data and editable attribute fields to streamline field operations on the next deployment.

Review of new GIS tools for assessments, analysis, and cartographic products should also be explored.

### 2.1.1. Spatial Data and Products Library: Organization

An organized format is the first requirement of a data and products library. Figure 5 shows an example of data organization that uses folders for base data and event data. Within the base data folder, additional folders for various data categories are created.

- Fire
- Hydrography
- Topography (Terrain)
- Climate (Meteorological)
- Land Cover
- Soils
- Biology
- Infrastructure
- Transportation
- Cadastral
- Imagery (or Remote Sensing)
- Org_Boundaries (Organizational and Political Boundaries)

The event data folder contains data, map products, tables, and other documents. Like in the base data folder, the event data folder has sub-folders for spatial data types (such as those shown in

Appendix 6.2, the Spatial Data Matrix), as well as for H&H modeling inputs and outputs (such as those shown in Appendix 6.3, the H&H Model Matrix). The data that are collected and placed here are specific to a wildfire or post-fire flood event, and can be further organized by affected watersheds or defined impact areas.

The structure shown in Figure 5 is just one example for organizing a data library. Other formats may use folders for data file types, like vector and raster. Another option is the creation of a geodatabase with feature datasets for the categories. The important value of a having good and consistent structure that works for the individual user is that datasets can be easily accessed, and the format can be easily understood and implemented by other users. Response to disaster events usually employs multiple personnel executing various GIS tasks, necessitating an organized spatial hub. Additionally, many agencies have the personnel respond on emergency deployments of a set duration. This means a transfer of knowledge must occur as the first responding staff end their tour and handoff to follow up personnel.

## Base Data

A collection of standard, widely applicable data should always be maintained as base data. Priority may be placed on regional-scale spatial data such as satellite imagery, soils and geology, landslide inventories, or hillshade products from LiDAR (10 m or better). These and other infrastructure data – like locations of utilities, drinking water supplies, or critical facilities – can be considered base data for emergency readiness. If these data are not readily available at the beginning of the fire response, it will likely be the responsibility of GIS staff to focus on collecting them, which could delay the actions needed to prevent further post-fire damage and potentially put lives at risk. See Section 2.1.2 for a discussion on common ways to compile and store available base data.

## Event Data

Event data are those data specific to a fire or flood after fire event. This includes information gathered early during the response timeline, such as the burn perimeter and soil impacts (BARC or soil burn severity mapping). There are rapid response tools for flooding and erosion analysis that can utilize estimates of burn severity and hillside slopes. A GISS will need to appropriately process these data for later use by an H&H engineer so that models can be used to identify areas at risk for flooding, debris flows, or other hazards.

### 2.1.2. Spatial Data: Collection and Updating

Spatial data collection revolves around describing the watershed's current status, including setting a baseline for pre-event conditions, and establishing the most current accounting for elements that may be impacted by floods and/or debris flows. As a wildfire event occurs, datasets are refined to the event boundaries for the initial assessments and analysis. H&H modeling will require inputs from several of these datasets. Higher modeling fidelity places the most importance on the terrain data. The better the spatial and temporal resolution, the better the quality of model outputs and analysis assessment.

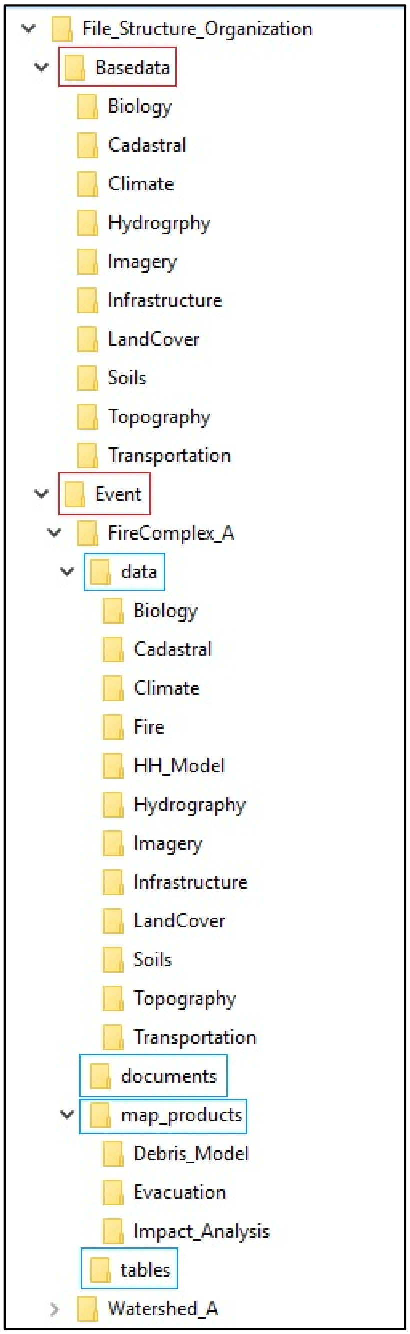


*Figure 5. Example organizational hierarchy for GIS data.*

A consistent naming convention is recommended such as description name, agency origin, and a date. Using underscores in place of spaces is a best practice. Also, the data name/path name length and number of folder trees can affect spatial analysis tool processing.

Metadata for the datasets acquired through download or electronic transmission should already exist. For datasets that are created or processed for analysis or modeling, metadata should include a good description, projection and coordinate system, value units, key field definitions, data creation methods, and data creation dates or modification dates. Listing contact information and data use restrictions are also strongly recommended.

### 2.1.3. The "Brick" – A Portable Data Library

During a fire incident, it is common to need several gigabytes of data for initial mapping preparation and later iterations. Incident Command Posts (ICPs) may be built in remote locations, so these data may not be accessible during an emergency if a responding GISS has no sufficient or reliable connection to the internet. It is thus advisable to prepare a workaround for this common scenario.

One such workaround is used by the USFS. USFS GISS personnel maintain an extensive collection of data on external hard drives, typically referred to as the "brick" or "toaster" (i.e., a data black box). The hierarchical data organization of these external hard drives is fairly standardized among Forest Service regions, which aids a GISS with familiarity and reduces time searching for data on the drive. In California, these bricks contain about 1.2 terabytes of data, including data from multiple Federal land management agencies, and select State, County, and City agencies and responsibility areas. Such data includes ownership, boundaries, land cover, topographic and digital orthophoto quadrangles, transportation routes, elevation products, municipal and political districts, fire history, facilities and utilities locations, a wide array of natural and cultural resource data, and a number of contact lists and reference materials. Also included are various necessary software, mapping tools, and printer/plotter drivers that may need to be installed on secondary or rental computers. Some of these data are standard and rarely change, but a significant portion must be updated at least annually. The brick also includes a master data inventory spreadsheet on the drive with metadata, source information, and general update requirements. The master data list and filing structure is too extensive to display here, but it is recommended that if a tool similar to an external hard drive brick is used, it should include all data that could be needed to respond to a fire and prepare for possible flooding. These data should be organized in a consistent manner that follows whatever standard protocol is prescribed by the agency that maintains that external hard drive brick.

This is merely one example that the USFS uses in order to meet blackout data needs, and has been an effective tool in supporting GISS work during wildfire responses. Notably, the external hard drive brick does not have a complete inventory of urban/suburban or other built environment infrastructure data – such as culvert, bridge, and structure locations – because these data are not typically available at the regional or State levels. Most of these data would likely reside at the County or municipal level or with other responsible agencies such as Caltrans. Since these are frequently the features most in harm's way, it is advisable to consider how much of this kind of data should be included in the master dataset and update schedule.

It must be known that some Federal agencies (Department of Homeland Security (DHS)/FEMA and Department of Defense (DOD) in particular) do not allow external devices to be connected to computers to prevent cybersecurity breaches. Security protocols such as these necessitates a different method of data sharing. In principle the limitations and needs among all responding agencies are the same: time is critical during a fire incident or its aftermath, and internet connectivity may not be available. For this reason, data needs should be thought out carefully and be prepared and updated in advance.

### 2.1.4. Pre-Event Assessment/Analysis and Cartographic Products

In the Preparedness and Pre-Event timeline, assessment and analysis may be requested to provide a general overview of hazards. Cartographic products can provide valuable information for Emergency Managers and serve as a good communication tool for Inter-Agency and public interactions.

Examples of these products are maps of watersheds or areas that are at "High Risk" for wildfire. Spatial data used for the threat determination include current drought intensity, forest density/age, tree mortality, and climate forecasts. Other factors may consider population, high volume roadways, power line proximity, and recreational lands, such as camp grounds and parks. The following dashboard example, Figure 6, is a screenshot taken from an online story map (https://fsapps.nwcg.gov/psp/npsg/). It is a national seven-day forecast produced by the National Interagency Fire Center (NIFC).

Another map product may be identifying watersheds susceptible to debris flows. This usually involves mapping areas that have had significant wildfires in the past five years, and includes an assessment of infrastructure and populations at risk.

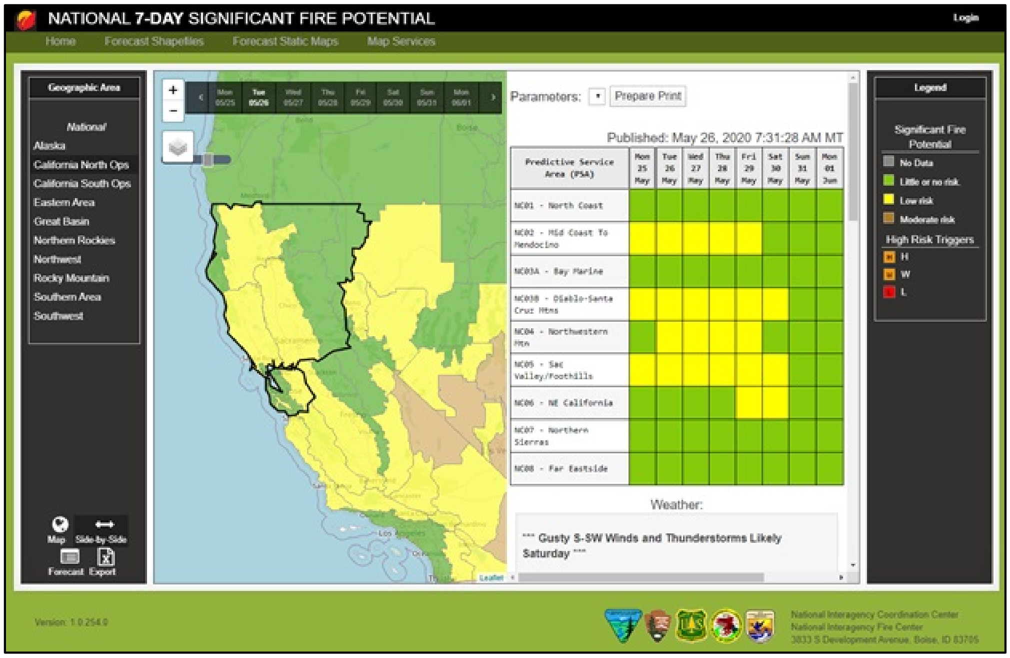


*Figure 6. Example NIFC dashboard showing fire potential.*

## 2.1.5. Field Applications

Field applications are typically developed during the offseason for the purpose of being fully vetted and available for field teams during deployment. These may include simple map-based tablet applications such as Avenza PDF maps, Survey 123, or more complex multi-layer applications, such as the Environmental Systems Research Institute's (ESRI) ArcCollector. Field applications may be used in all phases of deployment, such as:

- Documentation of fire damaged structures (damage assessment)
- Soil burn severity
- Values-at-risk and associated emergency protection measures identified during BAER and WERT response
- Documentation of stream channel conditions
- Infrastructure and mitigation measures for post-fire geohazard or H&H characterization
- Post-flood or debris-flow field observations to characterize inundation depths and extent

It is not necessary to identify geographic extent for potential field application deployment in the off-season as refinements can be made once a fire event occurs. Rather, the role of the GIS coordinator will be to work with the field teams to identify a list of required and optional base layers and attributed fields. These data should be prepared for the application and the application should be made ready for immediate deployment. To facilitate this, the GIS coordinator will need to prioritize development and field testing to ensure the agreed upon specifications will be available to field teams. Several cycles of development, testing, and refinement may be necessary.

## 2.2. H&H Impacts and Response

Fire events in California's steep terrain may have the potential to greatly impact immediate and neighboring communities, depending on the nature of the WUI. Possible impacts on large fires may include:

- Loss of life and infrastructure
- Increased flood risk (increased runoff volume and sediment movement)
- Increased debris flow risk
- Increased risk of rockfall
- Loss of downstream storage (sediment accumulation leading to filling of dams, debris basins, reduced levee freeboard)
- Altered soils (altered structure and infiltration, hydrophobicity, loss of beneficial bacteria)
- Soil erosion (surface sheet erosion, rilling, gullying, mass movement)
- Loss of vegetation and inception canopy
- Degraded water quality
- Impacts to critical species and habitats

It is very important to have base data and emergency response plans in place well before the fire. Involvement with state and local agencies can occur before a fire or fire containment. Coordination with the National Weather Service (NWS) is an example. The NWS establishes qualitative thresholds for flood warning precipitation rates.

Data used for post-fire geohazards, hydrologic, and hydraulic analysis (see Sections 2.1 and Table 3) will vary depending on the timeline and data availability (see Figure 4). During the fire, teams assess affected and downstream burn areas that form the basis for the type of analysis implemented. For example, evaluating changes to floodplain extents or debris flow potential related to infrastructure are estimated by pairing GIS and H&H data. Such data allow for rapid interpretation and will iteratively improve.

As post containment burn severity and soil data (event data) are added to baseline data during Time Tier 2, scientists and engineers will receive and process the event data for a wide range of uses. These uses may include sedimentation analysis for water quality, potential increases in flood inundation, erosion potential, changes in flood timing, and impacts to infrastructure. The preparation of spatial data may include the incorporation of new data such as LiDAR or aerial and satellite imagery. Understanding what baseline and event data are needed depend on the particular analysis and the software tools and methods applied.

### 2.2.1. Software Updates, Maintenance, and Training

There are a variety of H&H methods and software tools for users across the fire timeline. If the user is deriving a qualitative solution, a rapid response solution, or robust 3D model analysis, each effort will rely on one of three basic considerations:

(1) Timeline and timeframe
(2) Required sensitivity of the solution
(3) User familiarity of available tool/software

In all three considerations, having the software available and licensing up to date is crucial. If a rapid response is needed before or immediately after fire containment (Time Tier 1), event information is limited, and therefore the choice of modeling approaches is limited. If detailed analysis is needed and time is not a limiting factor, the user can select from more complex software options. An agency may appoint a staff member to prepare an H&H analysis and that staff member may be familiar with only one or two of the software options on hand. It is therefore worthwhile to dedicate time during the offseason (if available) to review updates to software and licenses, conduct maintenance on computer hardware, and re-familiarize staff with the software that's available to them, and how to use it.

# 3. Fire Event/Pre-Flood (Time Tier 1)

As previously mentioned, it is useful to consider fire response in a three-tiered timeline (Figure 4). This tiered timeline fits within and overlaps with the broader flood after fire planning context. These three time frames also dictate a range of resources, agency involvement, and responses. Response may vary depending on the fire location and severity.

The analyses that are needed after a fire can differ by time tier and purpose. During pre-containment (Time Tier 1), data that describe vegetation, soil, and infrastructure conditions may be limited to pre-fire and in-progress remote sensing conditions, BARC imagery, and rapid field-based post-fire observations. This is often when a GISS will begin collecting available data, as they identify infrastructure with BAER and WERT team data via rapid flood and debris flow assessments. Simplified and rapid-response models identifying flood, surface erosion, or debris flow risks are useful. If the fire occurs during California's dry season, this level of analysis may be sufficient, given that flood-triggering storms may be less likely that time of year. It is worth emphasizing, however, that a flood event can occur at any point within the fire timeline between pre-containment and subsequent years, therefore monitoring of weather conditions should be ongoing. Coordination with the NWS is crucial.

The following sections in this chapter detail the activities that are important during the earliest portions of fire response, to prepare for flood. These actions will be taken by GIS specialists, geologists, soil scientists, civil engineers, and hydrologists. The first section emphasizes the importance of interdisciplinary teams: the Federal BAER teams that are deployed by the US Forest Service and the Department of Interior, and the State WERT that are specific to the State of California.

Each stakeholder will operate under their own agency or contract guidelines and funding. For example, FEMA is activated only after a Presidential Emergency Declaration is made, which could occur as a wildfire is still spreading (Time Tier 1) or after fire containment when debris cleanup becomes a priority (Time Tier 2). FEMA may enlist the US Army Corps of Engineers (USACE) during this cleanup phase. During Time Tier 2, USACE GIS and H&H staff work with FEMA on location at the Joint Field Office (JFO) or remotely from USACE offices. USACE GIS and H&H support is limited to the FEMA funded timeline, which usually lasts approximately one month (occasionally two). Therefore, the fidelity of deliverables is based on a one month timeline, and the funds and data available during this period. During Time Tier 2, BAER and WERT team data are available, which typically allows for higher precision analysis of flood, erosion, sedimentation, and debris flow potential.

Detailed erosion, sedimentation, and debris flow studies are commonly prepared in Time Tier 3. Longer term soil and stream analysis occurs during this timeframe with potentially greater access to data and site monitoring. Mitigation efforts, residential debris, tree clearing, and best management practices (BMPs) are also analyzed during this timeline. A spreadsheet of common stakeholder responses across the timeline are listed in the Resource Timeline Matrix (Appendix 6.1).

Figure 7 depicts the hypothetical fidelity of H&H analytical methods across the response timeline. The modeling categories shown are not exhaustive, nor an endorsement of a particular method, but are reflective of how time and data availability relate to H&H resolution. For example, a stakeholder with an existing H&H model of pre-fire conditions may add value, given adequate time, to adjust the model and incorporate additional post-fire data. Likewise, a hydrologic or hydraulic model, can incorporate a simple bulking method if available data or time does not allow detailed study (e.g., Gusman, 2011). Simpler models and bulking methods can be refined over time. Rapid response and rule of thumb tools may not provide improvements in fidelity with more data or time. Detailed physical modeling and analytical methods are provided in Appendix 6.3, the H&H Model Matrix.

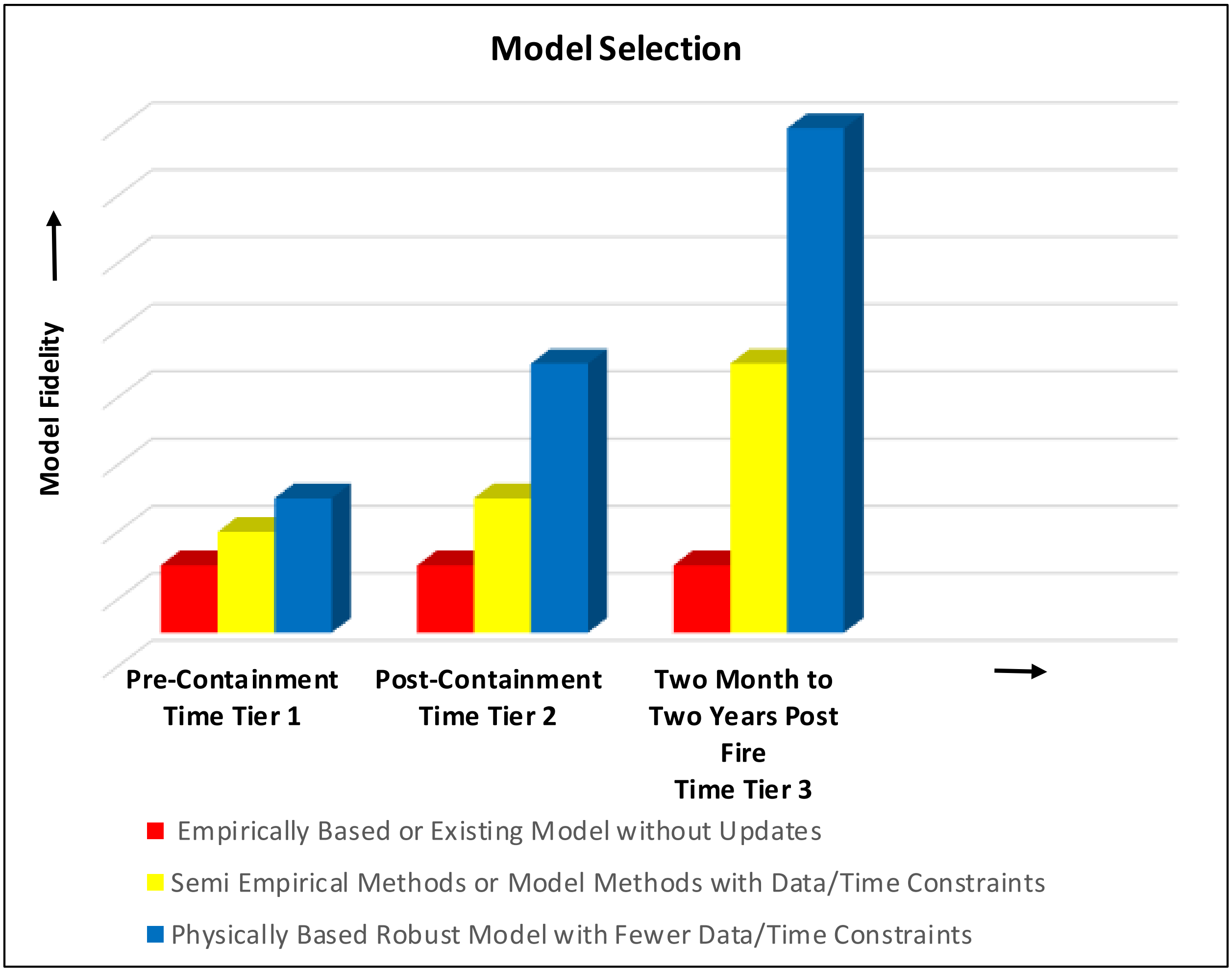


Figure 7. Generalized H&H modeling fidelity across timelines.

## 3.1. BAER and WERT

Federal BAER teams have been in existence since 1974, and are intended to address post-fire threats to life, property, and critical natural and cultural resources as a result of changed watershed conditions post-fire. The Department of the Interior (DOI) and Department of Agriculture have similar policies for BAER program responsibilities (USFS, 2020; DM 620). BAER is also known as "Emergency Stabilization" in the *Interagency Standards for Fire and Fire Aviation Operations* manual[1]. The objective of a BAER Assessment is to rapidly assess post-fire watershed conditions, identify BAER critical values (on Federal lands and as defined by agency policy), and apply risk assessment procedures for those values to determine if imminent post-fire threats warrant emergency response treatments. The USFS directs that all fires >500 acres, or smaller fires with suspected threats to BAER critical values, should receive some level of assessment. Where appropriate, emergency treatments are prescribed and implemented on Federal lands, with the objective to reduce risks to "acceptable" levels. BAER program responsibility is for Federal lands only, however most BAER teams assess the entire fire area regardless of ownership. Identified threats to non-Federal values are communicated to other appropriate agencies (e.g. NRCS, Caltrans) or other responsible jurisdictions (state, County, City) in an advisory capacity. However, the amount of time and effort spent evaluating non-Federal values downstream or in the wildland-urban interface is largely model-based and cursory compared to state WERT.

WERT have been utilized since 2015 to analyze risks in watersheds after wildfires and recommend actions. Post-fire assessments on non-Federal lands in California have been conducted by CAL FIRE and other State agencies using different approaches since 1956. WERT evaluations are narrower in scope than BAER assessments, and focus on selected wildfires that are anticipated to have significant life-safety and property risks from debris flows, flooding, and rockfall (CAL FIRE and CGS, 2020). WERT inventory values-at-risk (VARs) such as risks to life-safety, property and infrastructure, develop preliminary emergency protection measures, and rapidly conveys VAR locations and protection measures to local agencies (e.g., County department of public works, flood control districts) for implementation in the evaluation area (e.g., see Figure 8).

Often, WERT and BAER teams coordinate and share data on large fires that burn both Federal and State responsibility areas (SRA), each focusing on their respective geographic area (Figure 9). There are many similarities and some differences between the BAER and WERT programs, briefly described below, but both conduct rapid (e.g., 1-2 week) evaluations during Time Tier 1.

[1] https://www.nifc.gov/policies/pol_ref_redbook.html

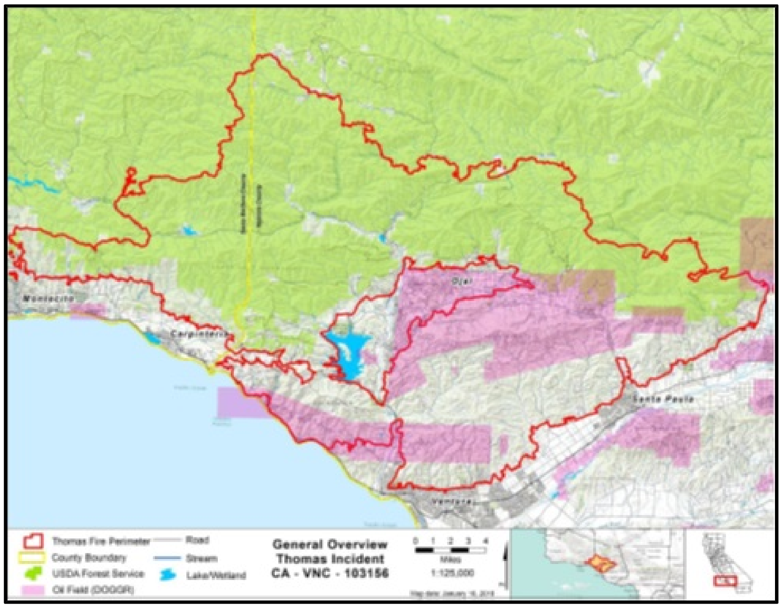


*Figure 8. Overview map of the Thomas Fire BAER and WERT evaluation area.*

Both WERT and BAER teams include professionals from many disciplines, with the membership dictated by the size and complexity of the fire. Typically, both these teams include geologists, hydrologists, civil engineers, and GISS. BAER teams also include soil scientists, botanists, archaeologists, and optionally wildlife and fisheries biologists and recreation specialists if needed.f

USFA BAER teams are usually composed of USFS employees, with exceptions, while DOI BAER teams are composed of professionals from several different Federal agencies (BLM, NPS, BIA, USFWS, USFS and NOAA). WERT are composed of employees from the California Department of Forestry and Fire Protection (CAL FIRE) and the California Geological Survey (CGS), and usually include staff from the California Department of Water Resources (DWR) and the California Regional Water Quality Control Boards (RWQCBs).WERT and BAER teams both begin the post-fire evaluation process by obtaining BARC maps (Figure 10), which are preliminary maps derived from satellite imagery (i.e., Landsat 8, Sentinel-2). BARC maps are made by comparing satellite-derived data for near- and mid-infrared reflectance values before and after the fire. This “raw data” – called differenced Normalized Bum Ratio (dNBR) – is then classified using specialized algorithms. BARC maps have been available since 2000, and the accuracy of BARC maps have been shown to provide BAER/WERT teams with an excellent starting point for the development of a final soil burn severity (SBS) map (Figure 11), which is used for erosion, peak flow, and debris flow modeling. The next step is to field check BARC maps for unburned/very low, low, moderate, and high soil burn severity using approaches described by Parsons et al. (2010). Final SBS maps can sometimes differ significantly from the BARC map (e.g., compare Figures 10 and 11 for the 2018 Woolsey and Hill fires), because satellites only observe reflectance values, not the more diagnostic belowground soil burn severity indicators.

**WERT**

- Very limited number of fires evaluated with significant SRA
- Focused evaluation for fires with life-safety and property risks from debris flows, flooding, and rockfall
- Rapid field assessment using current technology to locate VARs
- Rapidly develop and convey preliminary measures to local agencies for implementation

**USFS/DOI BAER**

- All fires >500 acres in size, or smaller with significant threats
- Broader evaluation of post-fire impacts that includes natural and cultural resources
- Development of prescriptions for VARs that can be rapidly implemented on Federal land (with funding)

*Figure 9. Comparison of WERT, USFS-DOI BAER main objectives.*

The higher the soil burn severity, the more susceptible the area is to rapid runoff, surface erosion, flooding, and debris flows. Key field indicators for soil burn severity include post-fire ground cover, soil structure, fine root condition, and soil char depth. Soil water repellency is also tested, but is generally not a reliable indicator for determining soil burn severity, as water repellant conditions are usually highly variable and may or may not correlate well with soil burn severity class on any given fire. Often there are only subtle differences in the characteristics for moderate and high SBS areas. These two categories are often lumped together for post-fire flood and debris flow modeling, but not for surface erosion modeling. If necessary, thresholds for one or more of the soil burn severity categories (i.e., unburned/very low, low, moderate, high) are adjusted within ArcGIS.

For larger fires with distinct climate and vegetation gradients or particular geologic types, the BARC data for different areas may need to be adjusted separately (e.g., by watershed) and re-combined for a contiguous SBS map. Some mistakenly consider the SBS map to be a hazard map or watershed response map, but it is not. It is a key modeling input for other hazard mapping products. Once the final field verified SBS map has been completed, three types of post-fire hazard assessments are typically produced by both the WERT and BAER teams:

- Peak flow/flood response
- Geologic Hazards, including debris flow, rockfall, and hazardous minerals
- Surface soil erosion

These products are in turn used to help determine the threat vector and level of risk to VARs.

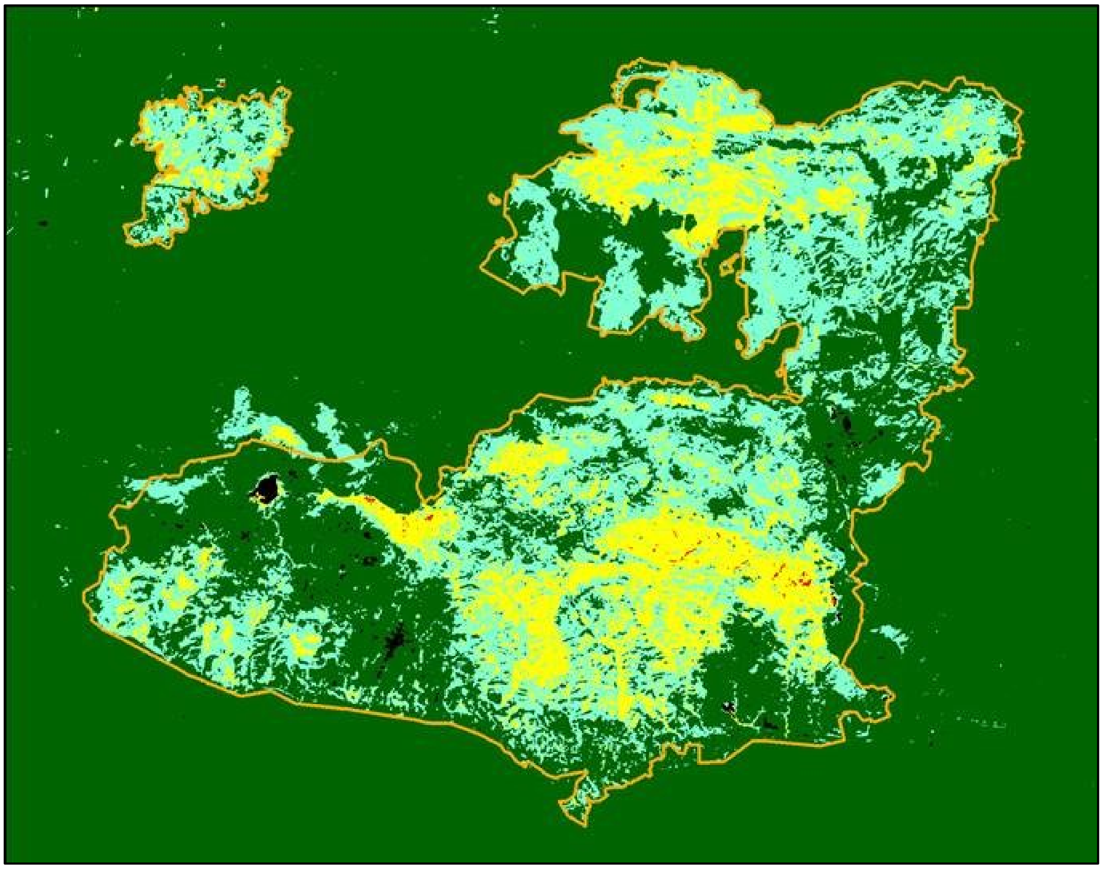

*Figure 10. BARC map from the 2018 Woolsey and Hill fires in Ventura and Los Angeles counties, California.*

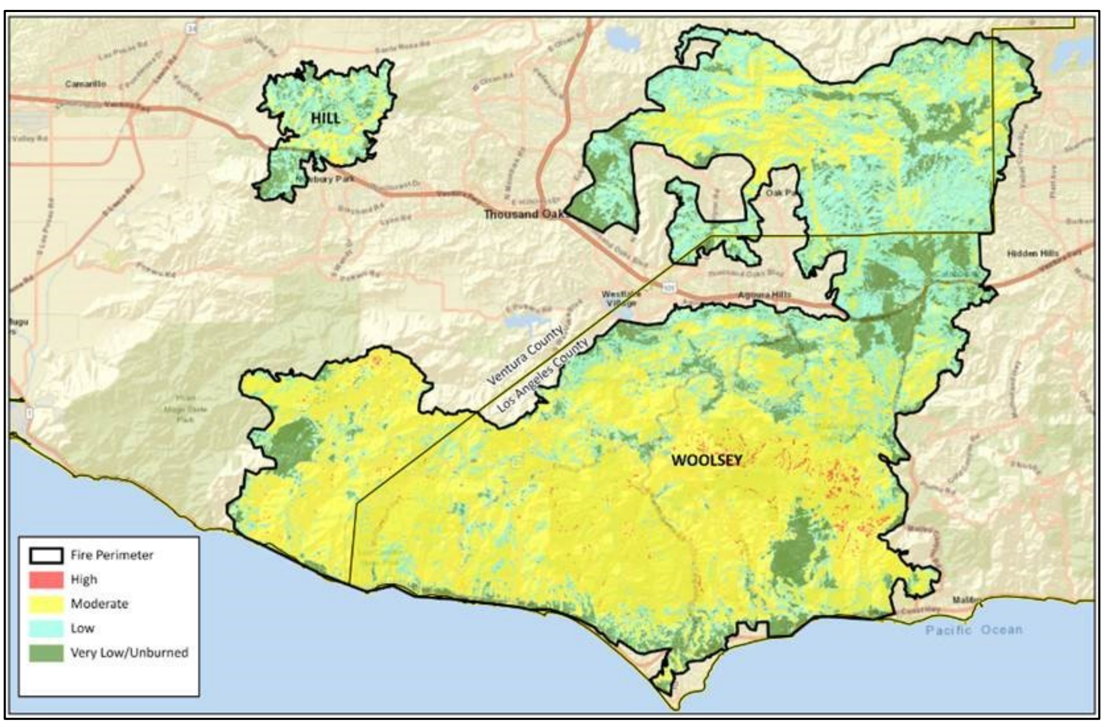


*Figure 11. Final SBS map for the 2018 Woolsey and Hill fires in Ventura and Los Angeles counties, California.*

## Peak Flow/Flood Response Modeling

Post-fire flood response is assessed at watershed scale, commonly 5$^{th}$ field to 8$^{th}$ field Hydrologic Unit Code (HUC), custom sub-watershed, or "pour point" watersheds[2] designated for individual areas or values to determine level of threat or risk at that point. Pour point watersheds are used to obtain a better understanding of the hydrologic response for smaller, individual areas at risk from flooding. If there are a high number of VAR sites in the fire area, pour point watersheds will be used to categorically sample subsets of VAR sites that may be expected to have similar response scenarios. Thus, typically they are not assigned for each and every VAR site. Some pour points are often at or relatively close to the fire perimeter. Some other smaller pour point watersheds within the fire perimeter may be delineated for particular high-value "targets" to determine level of risk, for example where there are life and safety values at potential risk.

Peak flow/flood response is determined by first estimating pre-fire flood flows for selected recurrence interval (RI) rainfall events typical for the local climate. Pre-fire flow estimates can be obtained in multiple ways. One common approach is to rapidly use the USGS StreamStats online tool (https://streamstats.usgs.gov/ss/). StreamStats is a Web application that provides access to GIS analytical tools, and can be used to rapidly delineate pour point drainage areas, obtain basin characteristics, and gather peak flow statistics using the California USGS regional regression equations (Gotvald et al., 2012). Alternatively, if a stream gaging station with a sufficiently long flow record (e.g., >20 years) is within the fire perimeter or a similar hydrological station is located near the fire, a flood frequency analysis can be performed (e.g., USGS PeakFQ program; https://water.usgs.gov/software/PeakFQ/) and the flow transference method (Waananen and Crippen, 1977) method can be used in an Excel spreadsheet. This method adjusts for the difference in drainage areas between the gaged station and the ungauged pour point watersheds to produce flow estimates. Usually only peak flows with relatively low recurrence intervals (RIs) (i.e., 2-year, 5-year, 10-year) are estimated, since flood flow prediction methods have lower confidence with larger recurrence interval events (e.g., 25-year, 50-year, 100-year) (Kinoshita et al., 2014). Also, treatments or protection measures that may be employed to manage risks to VARs become progressively less effective with larger RI events.

To estimate changes in post-fire peak flows, the percent area burned at unburned/very low, low, moderate, and high soil burn severity within each pour point watershed is determined using GIS analysis. Post-fire BAER and WERT peak flow estimates are rapidly generated using several different methods, depending on the fire location and data available. Methods include:

- Rowe, Countryman, and Storey (RCS) tables (Rowe, Countryman, and Storey, 1949 & 1954) for southern California

[2] Pour points for watersheds can be thought of as the bottom of a funnel – a watershed is delineated to include all uphill slopes that drain down to that particular point. This can be done using hillslope delineator tools in ArcGIS or hand digitized from topographic layers.

- USGS regional regression equations and the flow modifier method (Foltz et al., 2009)
- Moody USGS Analytical Method Equations (Moody, 2012)
- Wildcat5 (Hawkins and Barreto-Munoz, 2016)
- Regional 'rule of thumb' approaches (Table 2)

Recent research conducted by Kinoshita and Wilder at San Diego State University has shown that the RCS methodology is inaccurate for post-fire flow estimation for small watersheds (~750 to 8,650 acres) in southern California. Predictors with the highest importance include peak hourly rainfall intensity, soil burn severity, highest point in the basin, and basin shape (perimeter, circulatory ratio) (Wilder and Kinoshita, 2019). An improved rapid post-fire flow prediction method is under development.

Table 2. Selected BAER and WERT post-fire flow estimation methods (see Kinoshita et al., 2013).

| Post-Fire Peak Flow Estimation Approach | Applicable Location in California | Applicable Drainage Area | Advantages | Disadvantages |
|---|---|---|---|---|
| Rowe, Countryman, and Storey (RCS) (1949, 1954) | Southern California | N/A | Empirical method easy to use; well understood | Large inaccuracy for small watersheds; data not updated |
| USGS Regression Equations with Flow Modifier (Foltz et al. 2009) | No limitation | Better for large basins (>3200 ac.) | Easy to use; well understood | Must determine appropriate flow modifier (subjective) |
| Moody USGS Analytical Method Equations (Moody 2012) | No limitation | N/A | 30-minute rainfall intensity well correlated to peak discharge | Equations generated with little data from California |
| Wildcat5 (Hawkins and Barreto-Munoz 2016) | No limitation | <3200 acres | Best performing curve number (CN) method without calibration | User must specify the CN for pre- and post-fire conditions (uncertainty) |
| Regional 'Rule of Thumb' Methods | No limitation | N/A | Easy to use | Not validated, relies on professional judgment |

A bulking factor (Gusman, 2011) is often applied to the post-fire flow estimates generated from the methods listed above, as a conservative approach. Bulking by sediment can be extremely important during the first few post-fire winter periods (LACDPW, 2006a). Due to modeling uncertainties with these rapid approaches, absolute changes in flow volumes or peak magnitude for post-fire flows are usually not provided; rather an estimate of peak flow response is displayed to make a more informed determination on flood hazard. Relative increase of peak flows from one pour point drainage basin to another is judged to be more important for these rapid assessments, rather than the estimated absolute values of the peak flows (i.e., percent change in flows rather than flow rates in cfs). Changes in flood flow recurrence intervals are also commonly reported.

## Debris Flow Modeling

Wildfires can significantly alter the hydrologic response of a watershed to the extent that even modest rainstorms can produce debris flows. WERT and Federal BAER teams use the USGS debris flow products to further characterize values-at-risk. When the field verified SBS map is completed by the WERT or BAER teams, it is shipped electronically to the USGS Landslide Hazards Program staff in Golden, Colorado. They rapidly (<24 hours) develop estimates of the probability of debris flows and volume yields that may be produced by a design storm in the burned area. The model uses inputs related to basin shape, slope gradient, SBS, soil properties, and rainfall characteristics (Staley et al., 2016). Debris flow likelihood increases with:

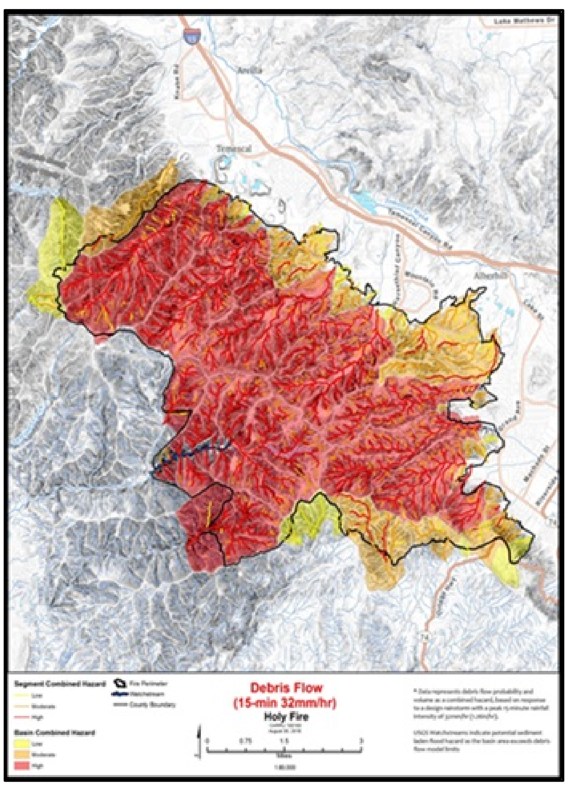


*Figure 12. Debris flow model map for the 2018 Holy Fire in Orange and Riverside counties.*

(1) Proportion of watershed with slopes greater than 43 percent and burned at moderate and high SBS

(2) Finer textured soil using the soil erodibility K-factor

(3) High-intensity, short-duration (e.g., 15-minute) rainfall

Post-fire debris flow likelihood, debris volume (Gartner et al., 2014; Staley et al., 2016), and combined hazards are estimated at both the drainage basin scale and in a spatially distributed manner along the drainage network within each basin (e.g., Figure 12). These are described as basin and segment probability maps, respectively. Hazard maps (e.g., Figure 13) are also produced for basins as the combination of probability and volume, referred to as combined hazard maps. The most hazardous basins show both a high probability of occurrence and a large estimated volume of material.[3]

[3] USGS debris flow model results for past wildfires are posted at: https://landslides.usgs.gov/hazards/postfire_debrisflow/.

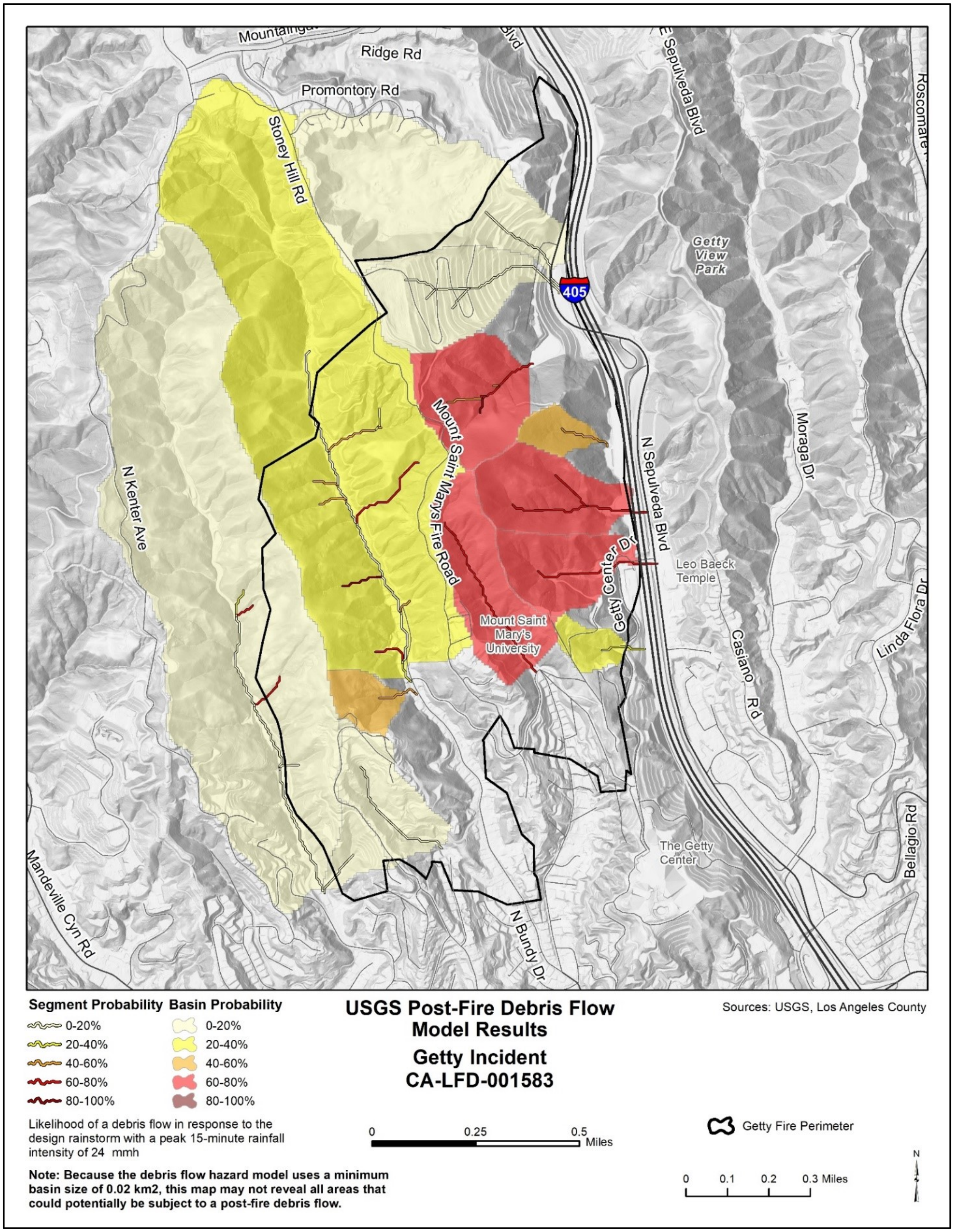


*Figure 13. Hazard map produced for the 2019 Getty Fire in Los Angeles County.*

WERT use debris flow model basin and segment maps from the USGS that are loaded onto tablets for field VAR evaluation, along with multiple other layers (e.g., SBS map, FEMA 100-year flood zone, LiDAR, permitted structures map, hydrography, roads, geology, soils, slope gradient, landslides) in the Esri Arc Collector application.

## Surface Erosion Hazards

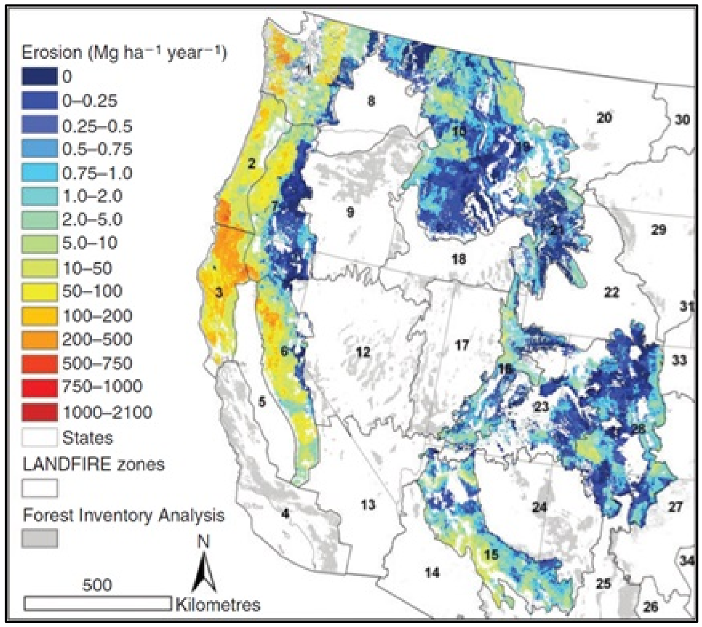


*Figure 14. Erosion rates in sloped areas across the western United States (Miller et al., 2011).*

WERT and Federal BAER teams model erosion estimates in two ways: hillslope erosion rates (what is detached and transported from the slope) and watershed sediment production (what enters the fluvial system, accounting for hillslope re-deposition). Peak flow/flood modeling and erosion modeling are usually set up using the same set of watersheds and sub-watersheds or pour points for direct source-area comparisons. The most commonly used model for WERT and Federal BAER teams is Batch ERMiT (Erosion Risk Management Tool). ERMiT is a Water Erosion Prediction Project (WEPP) web-based interface tool developed to predict surface erosion from pre- and post-fire hillslopes and to evaluate the potential effectiveness of various erosion mitigation practices (Robichaud et al., 2011).[4] WERT and Federal BAER teams calculate soil loss from erosion when needed for a specific VAR. ERMiT requires input for climate parameters based on:

- Location (PRISM interface)
- Vegetation type (forest, range, chaparral)
- Soil type (clay loam, silt loam, sandy loam, loam textures and rock content)
- Topography (slope length, profile, and gradient)
- SBS class (unburned, low, moderate, high)

This model provides probabilistic estimates of post-fire hillslope erosion from single recurrence interval “runoff events” by incorporating variability in rainfall characteristics, soil burn severity, and soil characteristics into each prediction (Robichaud et al. 2011). ERMiT only predicts rill and inter-rill erosion due to runoff events generated by precipitation.

---

[4] https://forest.moscowfsl.wsu.edu/fswepp/

There are many other erosion models and WEPP variants occasionally used by WERT and BAER teams, they are available tools that offer utility in many circumstances. These models which are attractive in modeling flow increases and hillslope erosion concurrently in the same model, which has obvious comparability-advantages. These erosion models include:

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

Any of the WEPP interfaces will provide reports after running a model. These reports can be copied and pasted into a spreadsheet. Additionally, a URL is provided that can be shared or referenced later. As an example, the Sediment Delivery report provides soil data, sediment discharge from the outlet and sediment delivery from the hillslopes. The discharge from the outlet is the sediment from the hillslopes that did not re-deposit on the hillslope or settle out in the channel before it made it to the point of discharge identified in the model. Using the WEPP PEP for a 4,500 acre area in the Camp Fire burn scar, one watershed generated 68,000 tons from the hillslopes and discharged 14,000 tons at the identified discharge point. One can infer from this that 54,000 tons settled out before the outlet.

Dry ravel can be the dominant erosion process in certain geologic terrains with soils having low- to no-cohesion. It occurs where slopes exceed the angle of repose (i.e., approximately 60 percent slope). A dry ravel model is under development for use in such areas. Dry ravel tends to accumulate in seasonally dry, high-gradient stream channels, which can greatly contribute to debris flow risk and volume yield with significant rain events (Lamb et al., 2011).

## Value-at-Risk Inventories and Report Generation

In addition to the three types of post-fire watershed hazard assessments, Value-at-Risk inventories are conducted by the WERT and BAER teams. Each team determines where potential VARs are located within and downstream of the fire perimeter using Google Earth imagery, local knowledge, helicopter, field observations and other mapping and satellite imagery. WERT staff often have 15-20 GIS data layers available on field tablets to rapidly query and overlay for verification of risk at specific VAR field sites. WERT conduct detailed, labor intensive VAR investigations throughout downstream housing developments to inventory individual sites at risk, or larger groups of houses at risk with a polygon designation. In addition to houses, VARs may include infrastructure facilities such as highways and low volume roads, power generation facilities, water conveyance structures, and recreational facilities (e.g. hiking trails, parks, campgrounds). Federal BAER teams are more focused on risks to VARs located on Federal lands but do conduct downstream/non-Federal land VAR inventories in a coarse fashion to characterize relative risk. They communicate with other Federal, State and local emergency managers and other cooperators, the calculated peak flow, debris flow risk, and soil erosion potential to jurisdictions downstream.

Federal BAER teams are not only focused on life-safety and property threats from flooding and debris flows, but a broader inventory of other types of VARs (e.g., critical natural and cultural resources).

*Figure 15. Woolsey Fire DOI BAER/WERT Coordination Field Meeting, Santa Monica Mountains (November 21, 2018).*

WERT members develop and digitally record VAR preliminary emergency protection measures (e.g., early warning system use, storm patrol, structure protection, channel clearance work near crossings, signage to close road crossings). This information is summarized in a detailed spreadsheet and as GIS shapefiles, which are rapidly disseminated to local agency representatives at a "close-out" meeting. A detailed final report is generated summarizing the physical setting, methods and modeling approaches, modeling results, and observations and recommendations. Report appendices include WERT contacts, GIS maps, the VAR spreadsheet, VAR information sheets, and photographs.

USFS BAER teams summarize their findings in a Final BAER Report. This report also functions as an initial funding request for emergency treatments (when needed) that are based upon the rapid assessment conducted. This document includes:

- Description of the burned area
- Detailed information on watershed conditions and predicted post-fire responses (flood flows, debris flows, surface erosion rates)
- Summary of the analyses conducted
- Critical values potentially at risk with attendant risk assessment (an identified critical value is not a VAR until the risk assessment process establishes unacceptable risk)
- VAR summary table
- Emergency treatment objectives and descriptions
- Estimated treatment and monitoring costs

The highest priority of this funding request is emergency stabilization in order to prevent further damage to life, property, or natural and cultural resources on Federal lands as a result of changed watershed conditions post-fire. The BAER program is not intended to repair fire-caused damages.

For the USFS, the BAER team works directly for the Forest Supervisor during the assessment phase. The BAER assessment is supposed to be completed within seven days of fire containment, so, on large and complex incidents, the assessment typically begins around 60-70% containment. This timeline is intended to be short so that necessary treatments can be implemented as rapidly as possible, and before future post-fire damaging events occur.

Once the assessment is complete, a closeout meeting is held with the Forest Supervisor and staff, and sometimes local agency representatives; a separate public closeout is common on high-public-interest fires. If the BAER team recommends treatments and the Forest Supervisor approves them, funding for treatments is requested. In addition, detailed specialist reports with accompanying GIS mapping products are generated to support the Final BAER Report. Common assessment reports are geologic hazards, soil resources, hydrology, engineering/roads, botany and invasive plants, and heritage resources. These specialist reports will usually have more detailed and useful information for future emergency response managers than the BAER Report.

DOI BAER reports are similar to the USFS reports, and include sections on watershed, wildlife, vegetation, infrastructure, cultural resources, and forestry. DOI BAER plans include funding requests. Emergency stabilization is a one year, emergency mitigation program, while rehabilitation is a long-term program to rehabilitate lands not likely to recover naturally. The emergency stabilization plan will specify only emergency treatments and activities to be carried out within one year following containment of a wildland fire. Generally, emergency stabilization activities are prescribed only within the perimeter of a burned area. They communicate with other Federal, State and local emergency managers the calculated peak flow, debris flow risk, and soil erosion potential to jurisdictions downstream.

The submittal timing of DOI BAER emergency stabilization plans often depends on the environment/landscape of the fire and the complexity; however, initial submission of the emergency stabilization plan must be shortly after the containment of a wildland fire in order to ensure credibility and to document the urgency of the situation. The initial emergency stabilization plan must be submitted within seven calendar days after total containment of the fire. If additional time is needed, extensions may be negotiated with those having approval authority.

In summary, Federal BAER teams and State WERT are the first boots-on-the-ground after a fire that meets their agency response parameters. They conduct rapid assessments of VARs, or "what's in harm's way", that are threatened by post-fire events. The rapid nature of assessment and modeling methods may be coarse for users of this toolkit. However, these teams rapidly produce reports and spatial products that help to identify VARs and high hazard areas in a geospatial context, and the preliminary information provided can help focus where more in-depth (Time Tier 2 and 3) modeling efforts should be employed for flood hazard prediction and emergency response planning efforts.

## 3.2. GIS (Time Tier 1)

In this part of the timeline, a wildfire is occurring and continues to burn, and its magnitude makes it apparent that disastrous consequences are going to result. The GISS or technician will be tasked to provide the situational awareness of the event. The initial focus will be on the wildfire event itself, understanding the scope and immediate impacts of the fire. Additionally, however, the impact of possible flooding in the burn area will be a secondary focus. Event data collection and organization will begin for the affected watershed(s) and downstream areas. The information may need to be updated as the wildfire expands. Preliminary assessments and analysis can provide immediate answers to the impact that could occur from a rain event. H&H staff will require watershed data to begin the cursory modeling of flood inundation and debris flows. Agency management and other officials will want to see cartographic products to visualize the event scope, and understand the areas at risk of impacts from floods after the fire. The products will require an understanding of what specific questions are being asked, and who the audience will be. Good communication between GISS, modelers, and management is key to collecting the right information, answering the important questions, and presenting them in an understandable format that informs the audience.

GIS team members have numerous tasks in the initial phases of a BAER or WERT deployment, including:

- Obtaining data consisting of:
  - A BARC map containing raster data that can be layered onto a variety of maps
  - A fire perimeter shapefile for the incident
  - ArcGIS layers needed for post-fire flooding, debris flow, and surface erosion modeling[5]
- Generating and printing on a plotter large-scale paper maps showing BARC soil burn severity classes, the complete road layer, and other features aiding in field identification. Geo-referenced PDF maps or equivalent base maps are to be made and loaded onto iPads/tablets with the Avenza PDF Maps application and the ArcGIS Collector application.
- Working with the field team to divide the fire area into pour point watersheds based on identified VARs for hydrologic analysis. The GISS will extract relevant data as part of this process (e.g., watershed drainage acreage, acreage burned at each soil burn severity category, etc.). This method should be set up as an automated GIS process.
- Following established data management procedures to include: file names, locations, metadata, versioning or archiving, and preserving the availability of final GIS data and products for retrospective studies.

[5] The purpose of each data type, their limitations, underlying assumptions, and their inter-relationships should be articulated as GIS metadata. The data may include, but are not limited to, topographic maps (current and historical); published geology maps; LiDAR (where available); Digital Elevation Models (DEMs); USGS peak flow information and reports; FEMA floodplain maps; DWR flood awareness maps; and fire history, CalVeg, GIS road, parcel, and hydrography layers.

- Ensuring that appropriate computer programs are available to conduct the field assessment, including ArcGIS and Adobe Acrobat Pro. Additionally, iPads or other GPS-equipped tablets are desirable their ability to input detailed field information. The GIS team member will ensure that appropriate software/apps, such as Avenza PDF Maps, ArcGIS Collector, and Google Earth, are installed on the tablets.
- Ensuring that field personnel are trained for proper data collection and data transfer. The GIS team member will be responsible for data management. If available, the GIS team member will incorporate data collection schema (fields) for field data collection software such as PDF Maps and ArcGIS Collector.

### 3.2.1. Event Data: Collection and Organization

The first task for GIS personnel is the collection and organization of data related to the wildfire event. There will be data specific to the wildfire, and data for the affected watershed(s) and downstream areas. Most data are publicly available through agency websites, but some may require direct communication between agencies. Data specific to the watershed and impacted population and infrastructure can come from the initial base data collection. Data collected will also be determined by assessment questions being asked, and products that are required. The following is a list of key datasets for collection, and they are also listed in Appendix 6.2, the Spatial Data Matrix:

- Fire Perimeter – This will be used to map the scope of the event, and identify the watershed(s) initially affected.

- BARC – Identifies the burned vegetation condition, and is categorized into four classes: high, moderate, low, and unburned/very low. After field verification and possible modification, this helps to determine the burn fire severity locations, and where debris flow risks can be highest.

- Terrain – This is used on the initial status maps to provide a sense of the topography in the affected area. It is also probably the most important data for H&H modeling. The better the resolution, the better the modeling detail. Datasets are readily available on the USGS National Map (TNM) website for download: 10-meter DEM, Interferometric synthetic aperture radar (IFSAR, 3 to 5 meter), and LiDAR (0.5 to 2 meter).

- Hydrography Data – The best available data will be the USGS National Hydrography Dataset (NHD). This database will have the most detailed rivers/streams and water bodies. Additionally, it has the delineated watershed boundary data (WBD) in HUC that can be used to select the affected watersheds. It will be used for the status maps, initial assessments, and H&H modeling. Additional hydrologic data like flood zones from FEMA's National Flood Insurance Program (NFIP) can be useful for the initial analysis of impacts, as well.

- Infrastructure – This category covers roads, railroads, bridges, culverts, flood control structures, and buildings. Creating subsets of these base data layers helps with quick assessments of assets that may be directly impacted by the fire, and secondarily by flooding and debris flows. Many of these datasets can be found on national, State, or local websites. They may also be part of an agency's own databases.

- Census and Boundary – Examples of data from this category are population centers, State/County/city boundaries, agency boundaries, tribal land, and political boundaries. Again, creation of subset data layers to the affected area can help expedite assessment and analysis, and provide management with information on which agencies and entities are directly impacted. It also identifies the officials that will be directly involved with the disaster.

- Land Cover – Using data layers from the National Land Cover Dataset (NLCD), as well as vegetation datasets, helps with the initial description of the affected area. It will also be used in the H&H modeling efforts by providing the pre-fire baseline.

These datasets may need to be updated regularly as the fire expands and impacts additional watersheds and communities. Using an established organizational format makes this task easier. Additionally, it is recommended to use a naming convention incorporating the event name, data name/description, agency origin, and a date obtained. Under the commonly fast-paced conditions of emergency operations, there may be little time for complete metadata documentation, so descriptive file names help. As a reminder, if the total path/file name length is too long, spatial analysis processes may not execute. Also establish a projection for the datasets that are commonly used for the area. Statewide Albers projections or State Plane Lambert Conic projections are the most used. Many raster datasets are unprojected or in Universal Transverse Mercator (UTM) coordinates, so it is important to remember that cells will be skewed when projected or reprojected. Vector data can be reprojected without consequence.

### 3.2.2. Event Status: Initial Assessments & Analysis

As the fire is occurring, management and officials are going to have a multitude of questions relating to the status of the event, and the possible flood after fire impacts. The following GIS assessment and analysis tasks can provide the initial answers, before a full H&H modeling study is required:

1. Identification of Impacted Watersheds – Start with the watershed boundary dataset (WBD) from the NHD database. The database has HUCs for boundaries ranging from two digit regions down to 12 digit subwatersheds. In this analysis, it is recommended to use the appropriate 8, 10, or 12 digit HUC polygons. Doing a simple intersection selection with the current fire perimeter will identify the watershed(s) and subwatershed(s) directly affected.

2. Identification of Rivers/Streams and Water Bodies – Using the NHD flow lines and water bodies datasets, the stream reaches, lakes, and reservoirs can be selected. Additionally, the stream lines can be used to identify the downstream watersheds that may also be impacted.

3. Identification of Impacted Population – In this analysis step, census category layers are used: census tract points, County parcels, structures, and city/County boundaries. Using the identified impacted and downstream watersheds, another simple selection process is used to the create subsets of impacted features.

4. Identification of Impacted Critical Infrastructure – This category assesses the schools, fire stations, police stations, airports, hospitals, hazard material sites, power plants, power lines, sewage treatment facilities, gas and oil lines, communication towers etc. Again this is strictly a selection of the features from HIFLD (Homeland Infrastructure Foundation-Level Data) databases that intersect affected watersheds.

5. Identification of In-Stream Infrastructure – This is an assessment of bridges, culverts, dams, diversions, weirs, levees, floodwalls, closure structures, and stream gauges. Many of these features can be found in the National Bridge Inventory (NBI), the National Inventory of Dams (NID), and the National Levee Database (NLD). Culvert data may be available from State or County transportation, public works, and/or flood control agencies.

6. Identification of Impacted Agency Assets – These are features that are specific to an agency. This can be infrastructure and cadastral, or personnel and working sites. As an example, the USACE uses the Corps Projects Notebook database for identification of projects and studies in the Civil Works and Military Programs.

After these items are identified as impacted features, initial analysis can done. Basic information might be the total watershed area impacted, and total counts for each of the assessment categories. A deeper analysis could be done using a distance proximity from the affected stream lines, or using the existing FEMA flood zones (see example in Figure 16). This analysis can provide estimates for population at risk, number of structures and critical infrastructure possibly impacted, which dams, bridges culverts, and roads are threatened. Deeper analysis could lead to initial H&H modeling requests. This is where a GISS needs to become an interpreter at times. In other words, listening to management questions and needs, and translating that into data that will be required by the H&H engineers for modeling, to get answers.

### 3.2.3 Event Status: Cartographic Products

Many cartographic products can be produced to convey the situational awareness and display the results of the analysis and assessments. The type and format of the product depends on the audience, questions or message, data restrictions, and software and/or hardware limitations. Many questions need to be asked before the product can be created:


*Figure 16. Example of a FEMA Flood Zone Map.*

Who is the audience?

- Internal Agency Management
- Inter-agency Collaboration
- H&H Teams
- Public Use

What's its purpose or use?

- Situational Awareness
- Decision Making
- Accountability
- Public Knowledge

What is the scope or extent to be represented?

- Regional View – State, Multiple Counties, Multiple Fires
- Event Specific – Large Fire covering multiple watersheds
- Community Specific – Population Center or Facility (Impact Area)

What are the data, software, and hardware limitations?

- Detail restricted at scales or FOUO (For Official Use Only)
- Digital Views – Online Maps, GIS Software, Google Earth, PDF Reader
- Printer/Plotter – Page Size, Color

The quality of a map will depend on time restraints, man power, data accessibility, data quality, and software and hardware. The following is quick list of map formats with notes on their capabilities and limitations.

Google Earth

- Built in base data (aerial imagery background only)
- Quick layer generation
- Intuitive interface
- Easily shareable
- Data attribute and categorization limitations

- Not recommended for 50+ records
- No analysis capabilities
- Not for hard copy printout

GIS file map with export to PDF

- Online base data
- Multiple background choices (aerial imagery, topographic, streets, etc.)
- PDF output easily shareable
- PDF can be set to toggle layers on/off and with attributes
- Designed for hard copy printout
- Designed for spatial analysis
- Requires GIS software and knowledge
- Edits required to be done in GIS software
- Map creation can take time

Online GIS Maps and Dashboards

- Easily shareable (URL link)
- Online base data
- Multiple background choices (aerial imagery, topographic, streets, etc.)
- Toggle layers on/off and with attributes
- Excellent for assessment accounting and display
- Capable of hard copy printout (not great)
- Can be designed with spatial analysis tools
- Requires additional GIS software and knowledge
- Edits required to be done in GIS software
- Data creation and uploads can take time
- Map/Dashboard design and creation can take a lot of time

A list of example maps for this time tier can be found in the GIS and H&H Output Products Matrix (Appendix 6.4). Figure 17 below is an example of a situational map of the Camp Fire for use by USACE Emergency Management.

## 3.3. H&H Event Checklist

Prior to the deployment of technical resources, basic information on the geomorphic setting is needed to develop a conceptual geomorphic process-based understanding of the area being evaluated. A preliminary geomorphic setting evaluation will help provide a framework for the modeling plan.

Certain physical processes dominate specific domains as a result of rainfall regimes, geology, slope, soil and regolith production, and soil burn severity. For example, concentration of flow may occur within ravines on first-order stream segments in the upper watershed, but flow behavior may differ more dramatically in sediment concentration and flow viscosity than with larger river systems. In watersheds with abundant sediment supply, where channel segments reach 10 to 15%, sediment concentrations typically reach those of debris flood and debris flows. When the channel bed is steeper than 20%, sliding-type en mass instability of the channel bed occurs (Rickenmann, 2016). Thus, in the absence of stabilizing bed structures, channels with bed slopes of more than 20% may be expected to produce debris flows where soils and hillslope regolith production are conducive (Rickenmann, 2016; DiBiasi and Lamb, 2020). Conversely, in gently sloping riverine environments, the armoring of channel beds tends to inhibit the production of sediment laden flows.

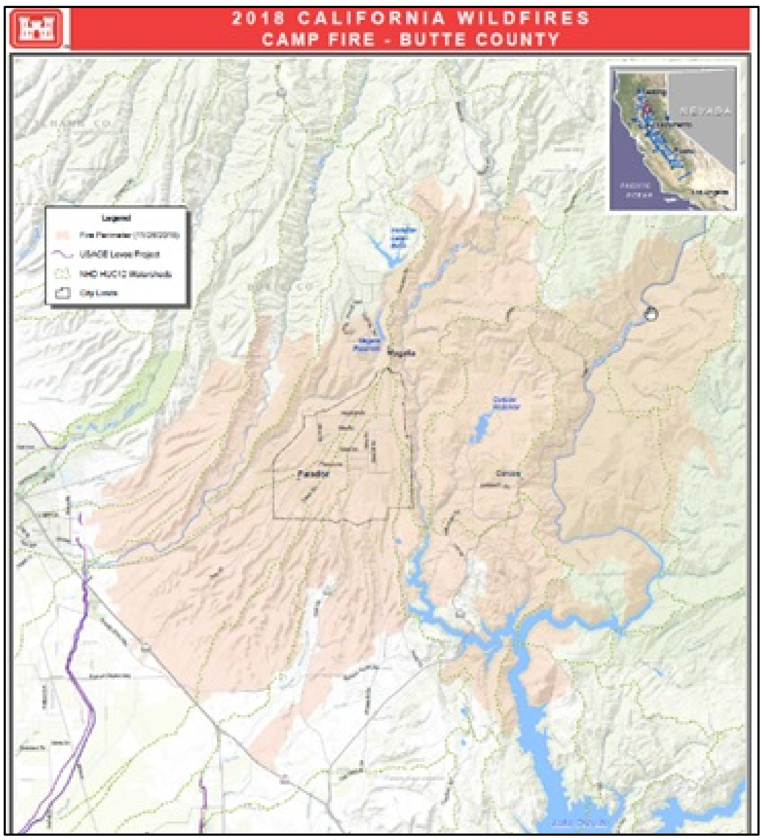


*Figure 17. USACE Situation Map used during the 2018 Camp Fire in Butte County.*

Depending on the type of problem being addressed and the staff involved, the geomorphic setting will need to be characterized to determine the position in the watershed and attendant energy of the environment. The BAER and WERT reports may provide key geomorphic observations in areas of interests. However, in the absence of BAER and WERT, a basic recognition of process domains is needed as indicated in Figure 18. Such an effort will require an interdisciplinary approach between geomorphologists and H&H modeling professionals. As described in the sections above, a review of watershed slope and sediment availability will help the practitioner understand potential flow behavior types at points of interest. However, a basic landform recognition should be used to determine whether the area of interest is within a tributary system such as a river, or a distributary system, such as an alluvial fan. In mountainous regions of the State that have high fire frequency, it is common to find alluvial fans of varying size that are constructed by a range of processes.

Alluvial fans are categorized as stream flow fans, debris fans, and composite fans based on their geomorphology (Bull, 1977; NRC, 1996). Debris flow dominated fans have steeper gradients (generally ≥6°) built by successive debris flows and sediment-gravity deposits, where water-borne sediment concentrations are generally greater than 50% by volume (Pierson and Costa, 1987; Iverson, 1997). Alluvial fans formed primarily by debris flow processes differ markedly from fans formed primarily by fluvial processes. The magnitude and consequences of debris flow impacts on the former are far more dramatic and impactful than turbid flood-flows on fluvial process dominated fans. This includes greater potential for channel avulsion near the fan apex (breaching and leaving the existing channel) and unpredictable overflow runout paths.

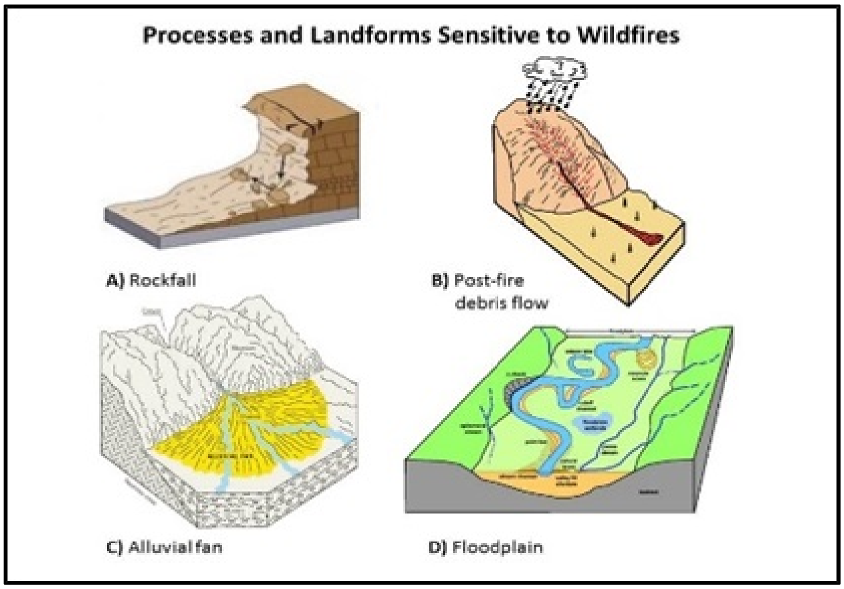


*Figure 18. Processes and Landforms Sensitive to Wildfires.*

A list of core data inputs for a majority of H&H methods are listed in Table 3. Data are used for flood, debris flow, and erosion analysis. Each fire presents unique concerns for evaluation, therefore product needs and inputs may vary according to location and event.

Table 3. H&H data checklist.

| DATA OWNER | DATA | DATA SOURCE |
|---|---|---|
| USDA/Multiple | Terrain/DEM (LiDAR or minimal resolution of 10 meter) | https://gdg.sc.egov.usda.gov/; https://www.arcgis.com/apps/View/index.html?appid=9204adf2fd1546379b845d163ef2544a |
| | Soil Data (Gridded format) | https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/home/?cid=nrcs142p2_053628 |
| | Basin Perimeter HUC | Subregions-map: https://gdg.sc.egov.usda.gov/ |
| USGS/USDA | Basin Perimeter HUC | https://www.usgs.gov/media/images/watershed-boundary-dataset- |
| CAL FIRE/USFS | Fire Perimeter Map | https://maps.nwcg.gov/sa/#/%3F/39.8212/-96.2709/4; https://www.nifc.gov/fireInfo/fireInfo_maps.html |
| Derived | (% Burn) Combined HUC and Fire Perimeter | GIS Staff |
| BAER /WERT/ USFS/USGS | BARC-Final Soil Burn Severity Map | https://www.fs.fed.us/eng/rsac/baer/barc.html |
| Derived | (% Severity per Category) Combines HUC and BARC | GIS Staff |
| USDA | Soil Data (Gridded format) | https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/home/?cid=nrcs142p2_053628 |
| Derived | (% Soil Type per HUC and Burn Severity) Combined HUC, Soil, and % Severity | GIS Staff |
| USGS/CAL FIRE | Land cover and Vegetation Cover Grid | https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap/science/land-cover-data-download?qt-science_center_objects=0#qt-science_center_objects; https://www.arcgis.com/home/item.html?id=35b4d77128264b3bacd31d9685f974b7 |
| Derived | (% Land cover per % Severity) Assigns post-fire infiltration and Manning's **n** | GIS Staff |
| USGS | Debris Flow Hazard Maps | https://www.usgs.gov/natural-hazards/landslide-hazards/science/post-fire-debris-flows |
| ESRI | Infrastructure Asset Maps | https://hifld-geoplatform.opendata.arcgis.com/ |
| NOAA | Precipitation Frequency | https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html |
| USGS | Streamflow Gaged/Ungauged | https://waterdata.usgs.gov/nwis/sw; https://streamstats.usgs.gov/ss/ |

### 3.3.1. Watershed Model Setup

Several models are currently used for comparing and predicting pre-fire and post-fire hydrologic impacts, some of which are described above in Section 3.1. However, the application of a suitable hydrological model depends on the major purpose of study, model complexity, and the data requirements. Major impacts that have been of common interest during post-fire assessment include peak flow magnitude and frequency, total runoff volume, peak timing for runoff and hyperconcentrated flow, along with the probability and volume of runoff generated debris flows. Runoff combined with debris-flow has caused considerable physical, environmental, and economic losses, including loss of human life; heavy damage to major infrastructures such as roads, pipelines, rail lines; and disruptions of major physical and electrical systems (e.g., Kean et al., 2019). Many field-based studies have shown that runoff-generated debris flows are common in steep burned watersheds where water floods can transition into debris flows (Cannon et al., 2001, 2003; Santi et al., 2008).

Flood hydrologic modeling options available to evaluate these post-fire related hydrological impacts vary from simple to complex, are statistical to semi/empirical to process-based, and were developed by different organizations. A brief description of various types of models used by different organizations, their applicability based on study purpose, along with their suitability, advantages, and limitations are summarized in the H&H Model Matrix included in Appendix 6.3. These models have been used during post-fire conditions mainly in the western U.S. Note that the modeling matrix for the H&H models does not encompass all hydrologic models that successfully simulate post-fire conditions. This flood after fire toolkit is focused on California and the models in the matrix are primarily those used in California. In addition, flash floods and debris flows are highly complex events that commonly occur in ungauged watersheds, and no predictive model will predict the magnitude and spatial extent of a flood or debris flow with a high degree of accuracy.

Common statistical models developed by regression analysis require minimal data and can be applied quickly to estimate hydrologic response in terms of peak runoff and debris flow (used in Time Tier 1). Major data requirements for these models include rainfall intensity and watershed characteristics, including soil parameters and soil burn severity which are directly contributing and most sensitive to runoff and debris flow. Although they are quick and easy to apply, most of the regression equations are semi-empirical or empirical, region-specific, event based, and developed for specific outputs. Therefore, these equations are more suitable for watersheds with underlying characteristics used in the equation. For simple and quick applications in regions with limited or minimum data availability, statistical models are well suited for evaluating pre-fire and post-fire watershed conditions.

Semi-distributed and distributed models are process-based models which incorporate the physical processes controlling the hydrologic response of the watershed (typically used in Time Tier 2). These models are more comprehensive and mainly developed for both event-based and continuous simulations while incorporating various components of the hydrological cycle and their interaction. Most process-based models use parameters that reflect measurable landscape characteristics and are spatially explicit, which makes it easier to understand the distribution of state-variables[6] such as velocity and depth at different time steps during a rainstorm (Blöschl et al., 2013). Therefore, structure of process-based models help to conduct hypotheses and parameter sensitivity testing, and to fully explore the importance of different factors in controlling the hydrologic response and explain the overall process controls within a watershed (Beven, 2001). However, complexity of these process-based models and their data requirements increase for fully distributed models as compared to semi-distributed models.

Most of these models are applicable to simple and complex watersheds. Depending on model parameterization and quality of available data, their application may be more suitable to specific regions (arid, semi-arid) and type of watersheds (small, large, rural, urban). Similar to empirical models, simple to moderate process-based models are rainfall/runoff dominated, where runoff or storm related processes are fully incorporated and parameterized compared to other processes. These models are suitable to simulate hydrograph properties including peak flow and runoff volume. The same sets of models could be used to simulate sediment transport, sediment volume and concentration with a lower to higher degree of limitations. The major inputs for this set of models include rainfall intensity (storm events) and watershed characteristics such as topography, soil, and vegetation. An actual profile of pre-fire and post-fire storm events along with delineated sub-basins within a watershed, and GIS-based distributed data are required for each sub-basin to simulate runoff mechanisms. Additional sub-basin and soil parameters (based on infiltration mechanism used), and channel characteristics are required to perform debris flow based simulation. Calibration of this type of model is less intensive compared to fully distributed models.

Complex models incorporate more physical processes and evaluate runoff and debris flow mechanisms using fully distributed models and process-based numerical models (typically used in Time Tier 2 or 3). These models are developed to handle multiple scenarios for a wide range of watersheds and storm events, and are capable of shorter or continuous simulation over longer periods. They incorporate detailed physical processes thereby requiring a large number of input parameters that complicates model parameterization and calibration. Therefore, the user needs a complete understanding of the overall hydrologic processes incorporated in the models and parameter sensitivity within those processes. Although these models are considered more accurate at representing physical processes as compared to statistical and semi-distributed models, the accuracy of results largely depends on measurement errors of the input dataset. Depending on the overall purpose of the study, major input parameters for this set of models require spatial and temporal distribution of higher resolution data for a wide range of watershed,

[6] State variables are those which define the current condition which could help predict future conditions.

soil, and storm characteristics. The major characteristics include: climate and weather (storm) data; soil texture, moisture, and temperature properties; land use and land cover; and types of land management practices. The major sources of higher resolution data include all newer technologies such as DEMs, LiDAR, radar, and satellite-based sources which are preprocessed through GIS and incorporated into the model.

Similar to semi-distributed models, additional data are needed to simulate soil loss, debris flow and debris flow paths, sediment transport and deposition, and sediment volumes/concentration. These data include:

- Channel characteristics
- Types of sediment and sediment concentrations
- Fluid viscosity
- Sediment and pollutant transport mechanisms (common in post-fire debris flow)
- Additional watershed features and debris contributing area
- Change in ground cover before and after the event

These models run at smaller time steps and process a larger set of higher resolution data to capture watershed physical processes more accurately, thereby making it data intensive, time consuming, and complex. This further complicates model parameterization, calibration, and validation.

Additionally, flow through a network of natural and constructed channels can be simulated using the non-Newtonian[7] flow module included in two or three dimensional (2D/3D) models and distributed hydraulic models (e.g., 2D/3D Adaptive Hydraulics Model (ADH), FLOW 2D/3D, and HEC-RAS). Using the non-Newtonian flow simulation module, flow and sediment yield produced from the watershed can be routed through the channels to predict the inundation boundaries, depths, and arrival time for a range of flood frequency hydrographs. These outputs can be an aid to decide areas to be protected or evacuated during an emergency response plan. In addition, the model can be used for the channel optimization design to increase the capacity of the debris basins and channels to convey the predicted sediment yield from the watershed.

During the post-fire condition (Time Tier 3), it is important to plan and implement solutions that can reduce potential physical, environmental, and economic losses. Hydrological models are available that incorporate several management options which help to evaluate the effectiveness of physical and management practices to address post-fire conditions. These include reduction in flood peak, volume and inundation, and soil erosion prevention and control. Models such as HEC-HMS (model used by USACE) provide management options for planned diversions and construction of physical water control structures (on/off stream detention) to reduce and store storm runoff volume. Models such as ArcSWAT provide options for pond and reservoir storage,

[7] Non-Newtonian fluids are those with viscosity that is dependent on the stress or pressure placed upon them. Some debris flows behave as non-Newtonian fluids.

along with land use and land management practices, to evaluate the impacts on runoff and sediment at a local and regional scale. Additional input data related to ongoing and planned management practices, size of storage, and location of diversions, are required to simulate current and future developments in with or without project conditions. This allows practitioners to evaluate the impacts of watershed management practices. Further detailed studies could be performed for the management option considered the best option to handle future post-fire runoff conditions.

### 3.3.2. Initial Modeling: Pre-Event Conditions

Rule-of-thumb and empirical methods used in estimating flood and debris flow risk can commence once fire damage severity and coverage are estimated. The degree of effort involved in higher fidelity modeling is related to preparedness and data availability. The modeling efforts follow an iterative methodology:

- Do models and associated input data exist now?
- If data and/or models exists, what are their capabilities and efficacies?
- If data and/or models do not exist, what am I analyzing and what do I need to do so?
- What level of fidelity do I need?

For example, a stakeholder may have an existing model used for water quality but the upstream model extents are located at a gage, and that gage is downstream of the upper watershed fire damage. This model would need to be extended. Perhaps both hydrologic and hydraulic models exist, but the inflows were based on a particular reservoir release assumption, such that the hydraulic model is suitable but the hydrologic inputs need adjustment. As another example, a modeled area may have been created before a dam or large development was built. These are just a few examples which emphasize that not all existing models fit the needs of today.

If a hydrologic, hydraulic, or combined model must be created from scratch, the user has to weigh the time and funds available against the analysis required. Does the model offer the fidelity to study erosion and mass wasting but the input data are unavailable in the time limits afforded? What is good enough? Given the data available at this time, what can I confidently conclude?

Table 3 describes the common input data needed in H&H analysis (simple to complex needs). Terrain, field verified SBS data, fire perimeter, soil data, land use, gage, and flow data are staples for most analysis.

## 4. Post-Fire/Pre-Flood (Time Tier 2 & 3)

As California's fire season continues to grow longer and drier, post-fire analyses are critical for evaluating flood risk in severely burned watersheds, particularly those with critical infrastructure and residences close to or within the fire perimeter. For some wildfires (e.g., those with significant values-at-risk), H&H analysis begins during Time Tier 2, after the fire has been contained and BAER or WERT data are available. The time the GISS and H&H engineers have to collect event data and analyze it will vary, depending on when the fire burned (i.e., summer vs. fall) and weather forecasts. They may need to produce maps, such as Flood Advisory Maps (Figure 19) rapidly after the fire is contained, or they could have months before the next major rain event is anticipated.

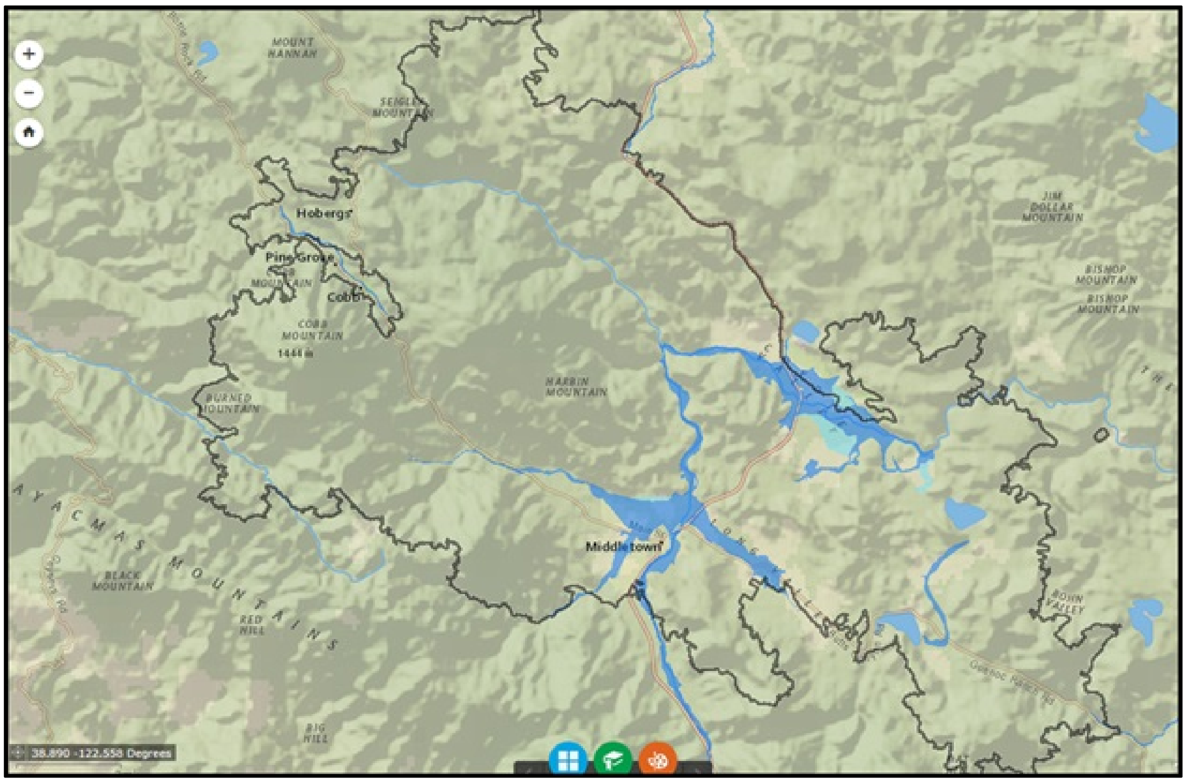


*Figure 19. Example Flood Advisory Map produced for the 2015 Valley Fire, Lake County, California.*

Regardless of how long Time Tier 2 lasts, modeling flood and debris flow hazards are contingent on the location and severity of the fire. Many large fires occur in remote locations with little downstream impacts. Therefore, the need for detailed H&H analyses may not exist. Efforts by local governments or communities to implement flood risk management measures or prescribed best management practices may be sufficient to prepare for post-fire runoff. Alternatively, if the fire was small but situated above a drinking water reservoir, a sediment study might be in order to better understand how the watershed – modified by wildfire – will react to significant storm events, and in turn effect the water quality in the reservoir. However, depending on the level of effort needed, these types of robust studies and analyses may be undertaken during Time Tier 3; months after the fire is contained (see Chapter 5).

Assuming terrain, land use, BARC, and fire perimeter data are available, there are three common methods of H&H response. Each method should compare pre- and post-fire conditions:

1) Hydrologic analysis only (with or without bulked flows)
2) Hydrology outputs (hydrographs) as inputs to hydraulic models (bulking used in either)
3) Hydraulic model using hydrograph or precipitation inputs (bulked or full sediment analysis[8])

The first method involves a hydrologic approach only, addressing primarily changes in watershed characteristics including soil infiltration and channel roughness. Changes in these factors will affect runoff volume and flood wave arrival time. Fire affected changes in runoff are not representative of every post-fire impact. Non cohesive soils and steep slopes in a watershed may dictate the addition of soil bulking to accommodate added flood volume. The modeler may choose a suitable method to incorporate bulking depending on available tools and techniques. For a series of examples, see the Ventura County's report on bulking factor methods in Gusman (2011).

The second method, which typically requires more time and effort, uses outputs from a hydrologic model to increase the accuracy of flow and precipitation inputs to the hydraulic model. For example, the input of a precipitation hyetograph in a hydraulic model will not include infiltration, canopy, or storage losses, which may be lacking necessary information. Running both hydrologic and hydraulic models generates products that can be verified against a historic event or known probabilistic flow, which adds confidence to the post-fire solution. Furthermore, based on post-fire conditions, the hydrologic or hydraulic model can be bulked in addition to hydrologic adjustments.

The third method solely utilizes a hydraulic model, which is commonly in a 2D format. A 2D hydraulic model is dependent on terrain. For this method, terrain dictates the watercourse for the modeler, and they do not need to invest time in calculating watercourse location, lengths, slopes, and Manning's **n** (roughness coefficient). Combining land cover, terrain, and burn severity grids further allows for quick input of roughness factors and is easily adjusted to post-fire conditions. Event-based post-fire condition grids are GIS products derived from post-fire observations. From these grids, moderate to high soil burn severity locations are paired with land cover, allowing for adjustments to roughness values using engineering judgment. For example, a pre-fire shrub or grassland roughness value will likely be reduced in the post-fire analysis. Changes to vegetation and land cover roughness can be expected based on burn severity and area. Depending on the types of products needed, sediment and debris solutions are modeled

[8] Sediment analysis often adds more time than Time Tier 2 allows

through bulking flows or sedimentation methods within the hydraulic model (See H&H Model Matrix for modeling examples).

Infiltration is incorporated in some hydraulic models, but generally speaking infiltration is not commonly a parameter in hydraulic models. See Appendix 6.3 for details on model use.

## 4.1. GIS (Time Tier 2 & 3)

By this point in the timeline, the wildfire is out, and its final magnitude and extent are known. Many agencies are now involved with recovery and cleanup after the fire event. While this is taking place, the focus for watershed teams shifts to the next possible disaster. With the final fire perimeter and burned area intensity determined, the affected watersheds and downstream areas can be finalized. Datasets needed for H&H modeling now have more complete information. A GISS will need to complete the collection and development of these datasets to hand them off to the modelers. The final assessments and analysis of impacts can be completed. Additional analysis using the post modeling outputs can be performed and cartographic products created. From the modeling efforts and analysis, information can be disseminated for decision making and public awareness to potential flooding impacts.

### 4.1.1. Event Data and H&H Model Preprocessing

After the fire is out, the extent of potential impacts is known. The final fire perimeter polygon will be used to identify the directly affected watershed(s), and determine the downstream impact areas. The terrain, hydrography, land cover, infrastructure, and census datasets collected from the previous timeline can be updated and finalized for these areas. Attention will now shift to providing H&H engineers with these updated layers, as well as, additional data to input into their models:

- Fire Perimeter – The final polygon perimeter will be used to identify the directly affected watershed(s), as well as determine the downstream impact areas.
- Soil Burn Severity (SBS) – The field verified version of the BARC data.
- Terrain – The terrain can be clipped to the area being modeled for faster model processing. Additional datasets like slope can be created by processing the terrain with ArcHydro or GeoHMS spatial tools.
- Hydrography Data – The stream network centerlines may need to be refined and updated for the inundation modeling. A stream gauge dataset for the watersheds should be compiled. The highest order watershed HUC level should also be defined to the affected area.
- Infrastructure – Datasets for bridges, culverts, and flood control structures should be updated for the defined impact area.
- Land Cover – Clip the National Land Cover Dataset (NLCD) and vegetation datasets to the modeling area. These datasets can be processed to produce Manning's **n** values in a raster format. Additionally, clip the Imperviousness and Tree Canopy rasters for the area.

- Soils – Clip the Gridded Soil Survey Geographic (gSSURGO) Database to the modeling area.
- Climate/Meteorological – NOAA rainfall event rasters (duration/return period). A climate gauge dataset should be compiled for the affected watershed and immediate surrounding watersheds.

The pre-model processed data:

- (% Burn) Combines HUC and Fire Perimeter
- (% Severity per Category) Combines HUC and BARC
- (% Soil Type per HUC and Burn Severity) Combines HUC, Soil, and % Severity
- (% Land cover per % Severity) Assigns post-fire infiltration and Manning's **n**

Post fire data layers produced by other agencies should also be collected for the spatial library for use in additional assessments and analysis.

- USGS Debris Flow Risk Polygons
- USGS Watch Streams
- Alert Gauges
- Structural Assessment (Fire Damage)
- Values at Risk

In addition, datasets will also be added from the geoprocessing results of impact analysis and post H&H modeling.

### 4.1.2. Event Updates: Assessments and Analysis

The questions coming from incident management and other officials related to potential flooding and debris flow will now be at a more granular level from the previous timeline. Information and statistics for specific impact areas will be requested. The questions will be more refined and may relate to recovery efforts in the area. Here are a few queries that may be raised:

- Are there any hazardous material facilities at risk?
- Debris clean up teams are in the area. What sites are at highest risk from flood?
- What are the critical bridges, culverts, and roadways that may impact evacuation routes?
- Where are the potential riverine choke points for debris flows? And what are the potential impacts to population and infrastructure upstream and downstream?
- How soon will a flood impact this area in a rain event?
- Are there any water supply threats from a potential debris flow?
- Where should we not place a temporary or long term shelter facility?

The quality of information to answer to these questions will depend how soon it is needed and to what level of detail (Time Tier 1 versus Time Tier 2). Immediate answers can be obtained from simple assessment analysis used in the previous timeline. As an example, existing 100-year flood plains and best available inundation mapping polygons can be used to query for the hazardous material sites found in the critical infrastructure layers of the HIFLD data. The polygons are limited in detail and are based on the watershed's pre-fire baseline. A higher quality analysis will require outputs from the modeling team that will have better input data, with current parameters of the wildfire impacts. This means it will take longer to produce a better answer. Impacts to population and infrastructure can be run using a suite of rainfall events based on duration (6 hr, 12 hr, 24 hr, etc.) and return period (2-yr, 10-yr, 100-yr, etc.)

It is important to document the datasets used and geoprocessing steps taken to complete the assessments and analysis so that these steps can be reviewed, refined, and repeated during future events

### 4.1.3. H&H Post-Modeling Processing and Cartographic Products

A multitude of products can be created from the assessment analysis and modeling efforts. Typically, a GISS will take the H&H model results to produce inundation depth grid rasters for the suite of rainfall events run. These rasters are displayed on the terrain for the watershed and defined impact areas, such as the example shown in Figure 20. Additional layers from the assessment analysis, like structures, bridges, culverts, and critical infrastructure can be added to cartographic products. Here are a few examples:

- USGS Debris Flow Combined Hazard Risk for a Selected Rainfall Return Period Event - Life Hazard Sites (BAER/WERT)
- USGS Debris Flow Combined Hazard Risk for a Selected Rainfall Return Period Event - Bridges/Culverts/Dams
- H&H Modeled Watersheds/Reaches for a Selected Rainfall Return Period Event - Population Centers and Critical Infrastructure at Risk
- H&H Modeled Watersheds/Reaches for a Selected Rainfall Return Period Event - Endangered Species/Sensitive Habitat at Risk
- Potential Debris Flow Choke Points and Simulated Debris Dam Inundation

More examples are shown in Appendix 6.4. As indicated in Section 3.2.3, the products can be presented as digital maps, or layers for Google Earth or online maps and dashboards.

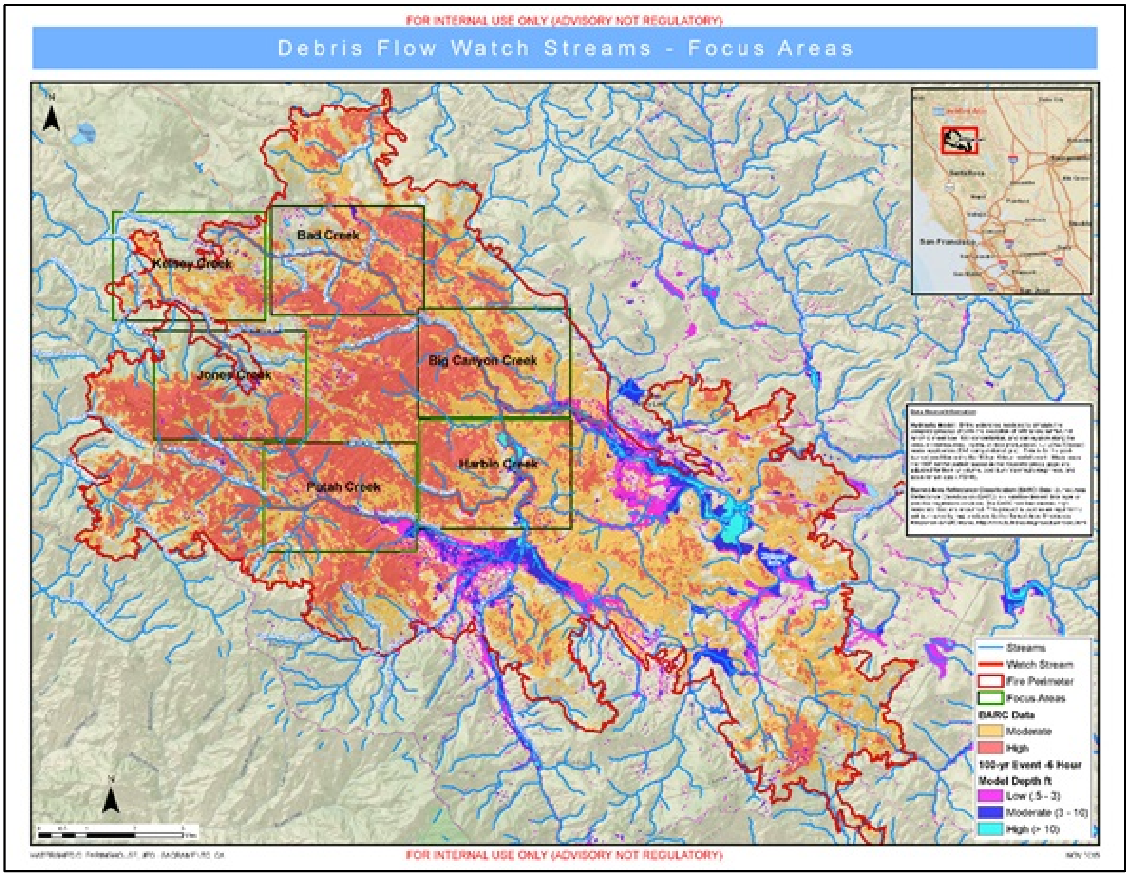


*Figure 20. Inundation depth map for debris flow watch areas in the perimeter of the 2015 Valley Fire in Lake County (USACE, 2015).*

Additionally, statistical information on the population at risk or types of critical infrastructure threatened can be represented in tables for reports. This can then be augmented with attributes such as watershed, County or City jurisdiction, political representation, and structural value. Economic analysis often requires GIS layers for processing. It can represent another aspect of the potential impacts to the community.

## 4.2. H&H Products & Deliverables

As H&H analyses are completed prior to a flood (Time Tier 2), a number of products are delivered. What products, and to whom they are delivered, will depend on the analysis conducted and end user requesting the analysis. The deliverable will be predicated by the requesting local, State, or Federal agency. For example, a long-term post-fire monitoring study, such as a groundwater study or best practices alternative, would require an in-depth set of products. In contrast, a short-term flood map used for evacuation would require less analysis than a long term sediment study. Regardless of the level of complexity, a typical suite of post-fire and pre-flood products includes:

- H &H models
- Terrain and GIS files used as input
- Raw data such as spreadsheet calculations, gage data, collected soil or survey data, assumptions, datum references, and As-Builts

The pace during emergency conditions places limitations on data availability and quality control efforts, especially during Time Tiers 1 and 2. For this reason, it is recommended that H&H solutions are presented as a "change in flow and sediment conditions," owing to post-fireconditions rather than presenting a solution as a deterministic forecast. Although H&H deliverables state these constraints, results and models are often picked up by unknowing users with an assumed expectation of accuracy. This can lead to decisions being made without complete knowledge of solution limitations and associated risks, resulting in liability issues. Therefore, stressing that H&H results during a response simply represent a 'delta' (potential change in flow or sedimentation), rather than a deterministic value, is paramount to the effectiveness of the response team and decision makers.

# 5. Post-Fire & Post-Flood

Wildfires bring drastic changes to the natural processes effecting geomorphology, hydrology, and sedimentation processes in the affected region. Producing complex and varying spatial effects to a given watershed and impact hydrology by removing the vegetation inception canopy, covering the surface through the production of ash and burned material, reducing organic binding material in soils, development of hydrophobic (or water repellant) soils, and altering the physical transport properties of the soils and sediments (Certini, 2005; Moody et al., 2009; Ebel et al., 2012). These processes all increase water and sediment runoff. Additionally, post-wildfire environments can cause a spectrum of hydrologic and sedimentation responses ranging from minor runoff events to catastrophic floods and deadly debris flows. The high sediment concentration and debris exacerbate damages from these events, which have been documented around the world (Rowe et al., 1954; Lane et al., 2006; Shin, 2010; Shakesby, 2011; Moody et al., 2013). These destructive flows often carry large boulders, trees, and even cars because of the high mass density and momentum of the sediment laden flows. Since burned regions lack vegetation to intercept and slow surface runoff produced by rainfall events, post-wildfire peak flows in those areas have reached all-time highs, with documented non-Newtonian hyperconcentrated (sediment laden) flows (Tillery et al., 2012; Rio Grande Water Fund, 2015).

*Figure 21. Hyperconcentrated ash flow in the Rio Grande River (Rio Grande Water Fund, 2015).*

It is important to determine what the dominant flood conditions (i.e., 'normal' flood, hyperconcentrated flows, mud flow, debris flow) for the watershed(s) of interest. Debris flows and similar non-Newtonian sediment-laden flow events are not only more destructive but behave quite differently from 'normal' flood events physically requiring different prediction and management approaches. Distinguishing between these types of flows is accomplished using both GIS-based data and field evidence. Additional information on both field and GIS-based identification can be found in Pierson (2004) and Jakob (2001).

Post-wildfire debris flow impacts are commonly defined by the given event probability, magnitude, and intensity. Magnitude is typically expressed as total flow, peak flow discharge, or area inundated. Intensity parameters are useful metrics since post-fire floods can vary along the flow path and include velocity, depth, runout potential, pressure, and force. Probability is the likelihood of an event to occur in the future, while frequency represent how often a given event occurs. Post-fire frequency-magnitude relationships are necessary for post-fire flood risk management because they allow approximation of the flood magnitude for any given return period. The post-fire frequency-magnitude can be determined using approaches developed by Cannon et al. (2010; see also Floyd et al., 2019).

## 5.1. GIS Reports

If a significant post fire flooding event occurs, the GISS will most likely be involved in the recovery efforts of that disaster. The assessment and analysis in the preceding timeline is being used to help make informed decisions for saving lives and mitigating damage to critical infrastructure and property. The tasks for a GISS post-flood will be to map the impacts (e.g, Figure 22) that have occurred. Questions from this scenario might be:

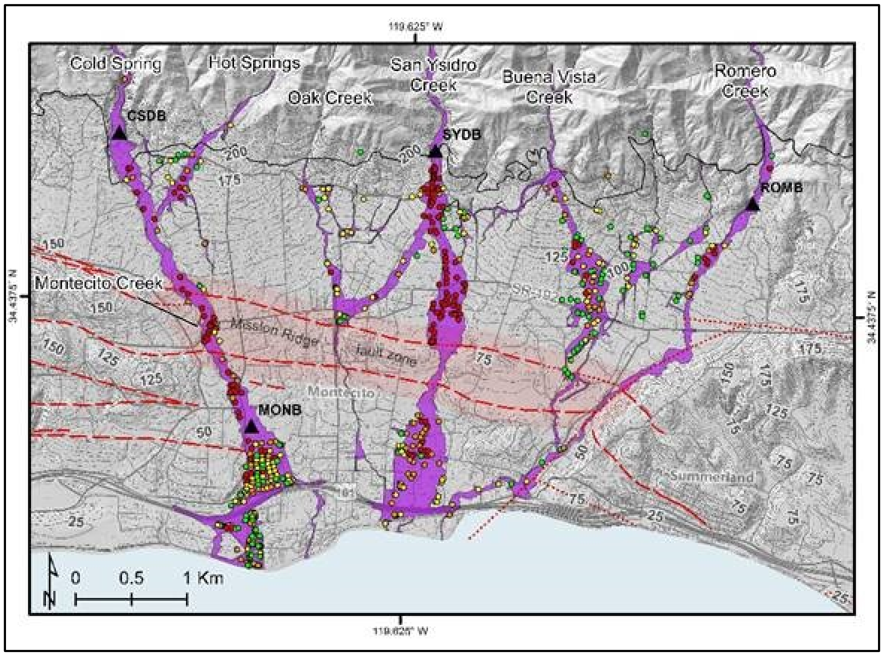


*Figure 22. Impact map for Montecito area after a debris flow event on January 9, 2018, that resulted from the 2018 Thomas Fire in Santa Barbara County.*

- How many homes were damaged or destroyed and where?
- What critical infrastructure were impacted?
- What bridges, roadways, or railways are impassible from debris?
- How has the geomorphic landscape changed? How are runoff and future inundation from rainfall events impacted?
- Are there riverine choke points creating impounded water and secondary inundation threats?

The final assessments for answering these questions and others will be used to produce cartographic products and tables for post-event reports. Additionally, the work will help to determine where to begin recovery efforts, and provide data for economic analysis.

A GISS will also be asked to contribute to After Action Reports (AAR), where lessons learned can be applied to future flood after fire events. Additionally, they may be asked to contribute long-term study reports and watershed restoration projects.

## 5.2. Long-Term Responsibilities

Large wildfires, especially in geomorphically sensitive regions, represent a significant perturbation to the natural system and dramatically alter the short-term hydrology, ecology, and sedimentation regimes. High geomorphic sensitivity describes systems that cannot handle large changes, such as fast vegetation growth (e.g., chaparral). The term implies a conditional instability in an environment, with the possibility of rapid and permanent changes (Phillips, 1999; Thomas, 2001). Effects on the hydrology can last years. Effects include increased runoff potential, changes to evapotranspiration, altered surface and substrate moisture storage, decreased watershed runoff lag time, higher peak flows, and reduced infiltration capacity (Neary et al., 2005; WEST, 2011).

In the years following a wildfire, vegetation type changes, rill and gully formation, mass wasting, and channel incision alter the hydrologic response. This often results in prolonged and dramatic changes in hydraulic and sediment impacts downstream. This requires long term monitoring and management plans.

Monitoring of burned watersheds and attendant storm rainfall induced flooding and debris flows is an important feedback on the results of risk assessments conducted after wildfire. In many regions of the State, there is little to no quantification of actual post-wildfire runoff events, including documentation of runoff, sediment concentrations, woody debris, avulsion characteristics, and storm rainfall rates and distribution. Because of this lack of data, it might be irresponsible to apply the methods described in this toolkit without consideration for developing a monitoring plan that may include, but not be limited to:

(1) Installation of rain gages

(2) Installation of stream gages

(3) Installation of radar

(4) Installation of monitoring cameras

(5) Performance of post-storm repeat observations

A basic monitoring plan that incorporates observation and measurement will greatly improve the ability to refine these FAF tools over time, resulting in incremental advancements in risk reduction.

In geoscience and engineering communities of practice in many parts of the western U.S. there is an increased demand for operational-based quantitative post-wildfire flood and debris flow analysis and guidance. This post-wildfire flood risk analysis and management are no trivial exercises. Post-wildfire flood and debris flow hazard analysis requires diverse interdisciplinary teams composed of experts from different organizations with varying technical backgrounds in fields such as, geology, geomorphology, sedimentology, soil mechanics, H&H, sediment transport mechanics, computation fluid dynamics, and ecology among others. Additionally, mitigation and management decisions should be based on approaches and computer models that facilitate both flood and debris flow modeling as part of post-wildfire flood risk management. These technical skills should be coupled with some basic understanding of the regulatory framework in a given wildfire affected area.

## 5.3. Conclusion

A major effort in today's response to wildfires is assessing and predicting wildfire effects on watershed hydrology in a timely manner, typically during and following the fire, so that necessary measures against flooding and erosion can be taken. For that purpose, agencies responding to wildfire need (a) fast but reliable methods to assess the risks of wildfire effects on watershed hydrology, and (b) quantitative methods to predict changes in stream flow and sediment yield for planning and designing flood and debris flow control measures. In addition, in most of the western arid and semi-arid United States, post-wildfire vegetation recovery can take years or even decades. This poses potential long-term management concerns for Federal, State, and local agencies beyond those of restoring watershed hydrology alone. With that in mind, this toolkit provides data, methods, and principles that will assist in evaluating changes to watersheds and flooding or debris flow risks that result from wildfires. However, this toolkit is still a single, narrowly-focused resource in a long-term management toolbox that is always expanding.

This toolkit is also a living document, which will benefit from being used in different environments by technical staff that have differing levels of experience in post-fire flood and debris flow modeling. This document tries to emphasize that many agencies and disciplines are needed to address the increasing risks of post-wildfire flooding and debris flows. Indeed, an interagency and interdisciplinary team of writers and reviewers, brought together through Silver Jackets, was needed to complete this first edition of the California Flood After Fire Toolkit. Future editions of this toolkit will benefit from more disciplines and agencies contributing to it, so that the complete picture of wildfire response can be realized.

# 6. Appendices

The following matrices were developed with two purposes in mind. First, they are broad summaries of material provided in the main body of this toolkit. They act as "quick reference" tools for those with experience in GIS, modeling H&H, or other related disciplines. They work well as a quick reference when an individual is already familiar with the general tasks or actions required for a flood after fire response.

Second, the matrices are supplemental reference material to the main body of the toolkit. They are self-referential, and as a result can be redundant with material provided elsewhere. This supports the matrices being able to act as a quick reference, however, they do not exist independently of the toolkit. Using the matrices as standalone tools or products demands and in-depth knowledge of wildfire response methods and requirements for flood after a fire preparation.

Descriptions of each matrix, including how to use them, are included in the following sections.

## 6.1. Resource Timeline Matrix (LINK)

Fire responses constitute a range of activities occurring throughout a temporal spectrum. The timeline commencing with fire initiation and can extend up to two years after fire containment. Responses vary by need, fire severity, fire location, stakeholder, allotted response time, funding, and potentially other factors. For purposes of this toolkit, the spectrum is divided into three general time tiers:

- Time Tier 1 begins with the fire (pre-containment) until shortly after containment
- Time Tier 2 begins after containment and covers FEMA activation (if it occurs) until approximately two months post-containment
- Time Tier 3 is considered a post fire monitoring, detailed study, and restoration period

Flooding can occur at any point along this timeline, and as fire seasons extend farther into the winter, floods and fires may become more coincident in California. Additionally, government and non-government stakeholder responses may vary according to the specifics of each fire and flood event that follows. The Resource Timeline Matrix included as this Appendix is not an exhaustive list of stakeholder needs and methods, but describes common fire response needs, methods, and sources used in a tabular format.

## 6.2. Spatial Data Matrix (LINK)

The Spatial Data Matrix is designed as a reference for data layers to begin a library for flood after fire response, analysis, and modeling. The data is grouped into seven general categories covering a number of data types. It provides a brief data description, metadata, data origination, typical format, if a map or feature service is available, where it falls in the timeline, whether it is used for H&H model inputs, last known web link, and notes on the data purpose. This Appendix should not be seen as complete, but rather as a living document that can be updated (possibly by the user) with information or links for existing datasets, or the addition of new layers.

## 6.3. H&H Model Matrix (LINK)

The H&H Model Matrix is organized by model complexity, which is based on their general use, data requirements, and incorporated processes. The first set of models are empirical models (1-4) which have fewer data requirements, and easier and quicker application, for estimating outputs. Empirical models are followed by semi-empirical models (5-10) which incorporate some linked hydrological processes, and therefore have additional data requirements. Both empirical and semi-empirical models may or may not be event based. These models are followed by a set of semi-distributed models (11-18), which are process-based and incorporate more physical and hydrological processes, thereby requiring larger sets of data for model simulations. Finally, the semi-distributed models are followed by distributed and fully distributed models (19-22). These are comprehensive, highly parameterized, and complex, and require a greater number of refined input parameters.

The first column of the H&H Model Matrix shows the name of model itself, or the agency/organization that provides model. The second column includes the major purpose (peak flow magnitude, peak timing, or debris flow) of the model, which is followed by the model's applicability to varying sized watersheds. The consideration of the size of watersheds was included based on model user manuals or field applications by different agencies/organizations. The infiltration/runoff mechanism column briefly summarizes the primary technique(s) incorporated into the model to handle the physical and hydrologic processes. This information should help users better understand the major mechanism and data needs for a particular model. The next column summarizes the major parameters, or dataset(s), required for the model. Although all data types are included in this column for most models, bear in mind that regression models usually only require data incorporated in the model and are directly related to the desired output. Major parameters are followed by an appropriate reference for downloading the model and assessing relevant documents and publications for model applications. The type of model (empirical, semi-empirical, semi-distributed, and fully-distributed) and simulation (event based/continuous) is defined in the next column. The final column provides various advantages, disadvantages, and limitations of the model.

## 6.4. GIS and H&H Output Products Matrix (LINK)

This Appendix provides examples of cartographic products that are usually produced during a wildfire response. The products are divided into the 4 time periods: Pre-Fire Offseason, Fire Event/Pre-Flood (Time Tier 1), Fire Event/Pre-Flood (Time Tiers 2 and 3), and Post Fire/Post Flood. This matrix should not be seen as complete, but rather as a living document that can be updated, by the user if applicable, with additional cartographic examples or work products

## 7. References


Beven, K. 2001. On hypothesis testing in hydrology. Hydrol. Processes, 15(9), 1655–1657.

Blöschl, G., M. Sivapalan, and T. Wagener (Eds.). 2013. Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales. Cambridge Univ. Press, NY.

Bull, W.B. 1977. The alluvial fan environment: Progress in Physical Geography, 1, p. 222-270.

CAL FIRE and CGS. 2020. Draft procedural guide for Watershed Emergency Response Teams. Sacramento, CA. 62 pp.

CAL FIRE. 2019a. Incidents. Retrieved from https://fire.ca.gov/incidents/2019/.

CAL FIRE. 2019b. Camp Fire. Retrieved from https://fire.ca.gov/incidents/2018/11/8/camp-fire/.

Canfield, H.E. and D.C. Goodrich. 2005. Suggested Changes to AGWA to Account for Fire (V2.1). Southwest Watershed Research Center, U.S. Department of Agriculture, Agricultural Research Service, Tucson, AZ.

Canfield, H.E., D.C. Goodrich, and I.S. Burns. 2005. Selection of parameters values to model post-fire runoff and sediment transport at the watershed scale in southwestern forests, American Society of Civil Engineers Watershed Management Conference. American Society of Civil Engineers, Williamsburg, VA., pp. 1-12.

Cannon, S.H., R.M. Kirkham, and M. Parise. 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology, 39(3), 171–188.

Cannon, S., J. Gartner, C. Parrett, and M. Parise. 2003. Wildfire-related debris-flow generation through episodic progressive sediment bulking processes, western USA, in Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation, pp. 71–82. Millpress, Rotterdam, Netherlands.

Cannon, S.H., J.E. Gartner, D. Parret, and M. Parise. 2003. Wildfire related debris flow generation through episodic progressive sediment bulking processes, western U.S.A. In: D. Rickenmann and C.L. Chen (Eds.). Proceedings of 3rd International Conference on Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment, September 10-12, Davos, Switzerland, pp. 71-82. Millpress, Rotterdam, Netherlands.

Cannon, S.H., J.E. Gartner, M.G. Rupert, J.A. Michael, A.H. Rea, and C. Parrett. 2010. Predicting the probability and volume of post-wildfire debris flows in the intermountain western United States. Geological Society of America. Bulletin 122(1/2), pp. 127-144.

Cerrelli, G.A. 2005. FIRE HYDRO, a simplified method for predicting peak discharges to assist in the design of flood protection measures for western wildfires. Watershed Management Conference - Managing Watersheds for Human and Natural Impacts: Engineering, Ecological, and Economic Challenges. G. E. Moglen, Ed. American Society of Civil Engineers, Williamsburg, VA, 935-941.

Certini, G. 2005. Effects of fire on properties of forest soils: A review. Oecologia, v. 143, pp. 1-10.

DiBiasi, R.A., & M.P. Lamb. 2020. Dry sediment loading of headwater channels fuels post-wildfire debris flows in bedrock landscapes. Geology, 48(2), p. 189-193.

Ebel, B.A., J.A. Moody, and D.A. Martin. 2012. Hydrologic conditions controlling runoff generation immediately after wildfire. Water Resources Research, 48, p. 1-13.

FEMA. 2003. Hydrologic & Hydraulic Methodology used to Estimate Post-Burn Floodplain Hazards. Federal Emergency Management Agency (FEMA). Report # FEMA-1498-DR-CA, 4 pp.

Flanagan, D. C., and M. A. Nearing. 1995. USDA Water Erosion Prediction Project hillslope and watershed model documentation. NSERL Report No. 10. West Lafayette, IN: USDA-ARS National Soil Erosion Research Laboratory.

Floyd, I.E., M. Ramos-Villanueva, R.E. Heath, and S.W. Brown. 2019. Evaluating post-wildfire impacts to flood risk management (FRM): Las Conchas Wildfire – New Mexico. ERDC/TN RSM-19-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center. DOI: 10.21079/11681/32910.

Foltz, R.B., P.R. Robichaud, and H.H. Rhee. 2008. A Synthesis of Post-Fire Road Treatments for BAER Teams: Methods, Treatment Effectiveness, and Decision Making Tools for Rehabilitation. USDA FS Rocky Mountain Research Station. Moscow, ID.

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

Gartner J.E., S.H. Cannon, and P.M. Santi. 2014. Empirical models for predicting volumes of sediment deposited by debris flows and sediment-laden floods in the transverse ranges of southern California. Engineering Geology 176:45-56, DOI: 10.1016/j.enggeo.2014.04.008.

Gotvald, A.J., N.A. Barth, A.G. Veilleux, and C. Parrett. 2012. Methods for determining magnitude and frequency of floods in California, based on data through water year 2006. U.S. Geological Survey Scientific Investigations Report 2012–5113. Retrieved from http://pubs.usgs.gov/sir/2012/5113/.

Gusman, A.J. 2011. Sediment/debris bulking factors and post-fire hydrology for Ventura County. West Consultants, Inc. San Diego, CA. May 2011. Retrieved from https://docplayer.net/26973239-Sediment-debris-bulking-factors.html.

Hawkins, R.H., and A. Barreto-Munoz. 2016. Wildcat5 for Windows, a rainfall-runoff hydrograph model: user manual and documentation. Gen. Tech. Rep. RMRS-334. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Retrieved from https://www.fs.usda.gov/treesearch/pubs/50557.

Higginson, B., and J. Jarnecke. 2007. Salt Creek BAER—2007 Burned Area Emergency Response. Unita National Forest, Provo, UT.

Iverson, R.M. 1997. The physics of debris flows. Reviews of Geophysics, 35, p. 245-296.

Jakob, M. 2005. Debris-flow hazard analysis. In: Debris-flow hazards and related phenomena, pp. 411-443. Springer, Berlin, Heidelberg.

Jennings, M. E., W.O.J Thomas, and H.C. Riggs. 1994. Nationwide Summary of US Geological Survey Regional Regression Eqs. for Estimating Magnitude and Frequency of Floods for Ungauged Sites, 1993. USGS Water-Resources Investigations Report 94-4002, 196 pp. 94-4002, USGA.

Kean, J.W., D.M. Staley, J.T. Lancaster, F.K. Rengers, B.J. Swanson, J.A. Coe, J.L. Hernandez, A.J. Sigman, K.E. Allstadt, and D.N. Lindsay. 2019. Inundation, flow dynamics, and damage in the 9 January 2018 Montecito debris-flow event, California, USA: opportunities and challenges for post-fire risk assessment. Geosphere, 15. Retrieved from https://doi.org/10.1130/GES02048.1.

Kinoshita, A., T.S. Hogue, and C. Napper. 2013. A guide for pre- and post-fire modeling and application in the western United States. USDA Forest Service, National Technology and Development Program, 1325 1802—SDTDC. Retrieved from https://bluegold.sdsu.edu/docs/2014_KinoshitaHogueNapper_GuideforPreandPostfireModeling.pdf.

Kinoshita, A.M., T.S. Hogue, and C. Napper. 2014. Evaluating Pre- and Post-Fire Peak Discharge Predictions across Western U.S. Watersheds. Journal of the American Water Resources Association (JAWRA) 1-18. DOI: 10.1111/jawr.12226.

Laber, J. 2018. An Overview of the January 9, 2018 Flash Flood and Debris Flow Event in Montecito, CA. Retrieved from https://www.alertsystems.org/presentations/Conf2018/Session1-Recent_Events/Laber_REC.pdf.

Laflen, J. M., W. J. Elliot, J. R. Simanton, S. Holzhey, and K. D. Kohl. 1991. WEPP soil erodibility experiments for rangeland and cropland soils. J. Soil Water Cons. 46(1): 39-44.

Lamb, M.P., J.S. Scheingross, W.H. Amidon, E. Swanson, and A. Limaye. 2011. A model for fire-induced sediment yield by dry ravel in steep landscapes. Journal of Geophysical Research. Vol. 116, F03006, DOI: 10.1029/2010JF001878.

Lancaster, J.T.; T.E. Spittler, and W.R. Short. 2015. Alluvial fan flooding hazards: an engineering geologic approach to preliminary assessment. California Geological Survey, Special Report 227, 46 p.

Lane, P.N.J., G.J. Sheridan, G.J., and P.J. Noske. 2006. Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia. Journal of Hydrology 331, p. 495-510.

Los Angeles County Dept. of Public Works (LACDPW). 2006a. Hydrology Manual. Retrieved from https://dpw.lacounty.gov/wrd/publication/engineering/2006_Hydrology_Manual.pdf.

Miller, M.E., L.H. MacDonald, P.R. Robichaud, and W.J. Elliot. 2011. Predicting post-fire hillslope erosion in forest lands of the western United States. International Journal of Wildland Fire 20: 982-999.

Moody, J.A., D.A. Kinner, and X. Ubeda. 2009. Linking hydraulic properties of fire affected soils to infiltration and water repellency. Journal of Hydrology, v. 379, p. 291-303.

Moody, J.A. 2012. An analytical method for predicting post wildfire peak discharges. U.S. Geological Survey Scientific Investigations Report 2011–5236. Retrieved from https://pubs.usgs.gov/sir/2011/5236/.

Moody, J.A., R.A. Shakesby, P.R. Robichaud, S.H. Cannon, and D.A. Martin. 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth-Science Reviews 122, p. 10-37.

National Research Council (NRC). 1996. Alluvial Fan Flooding. Committee on Alluvial Fan Flooding, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources - National Research Council. National Academy Press, 172 pp.

Neary, D.G., K.C. Ryan, and L.F. DeBano. 2005. Wildland fire in ecosystems: effects of fire on soil and water. USDA Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GRT-42-Volume 4, Ogden, UT.

NOAA. 2015, August 26. Risk of very large fires could increase sixfold by mid-century in the US. Retrieved from https://www.climate.gov/news-features/featured-images/risk-very-large-fires-could-increase-sixfold-mid-century-us.

O'Brien, J., P. Julien, and W. Fullerton. 1993. Two-dimensional water flood and mudflow simulation. J. Hydraul. Eng., 119(2), 244–261.

Parsons, A.; P.R. Robichaud, S.A. Lewis, C. Napper, and J.T. Clark. 2010. Field guide for mapping post-fire soil burn severity. Gen. Tech. Rep. RMRS-GTR-243. Fort Collins, CO. USDA, Forest Service, Rocky Mountain Research Station. Retrieved from https://www.fs.fed.us/rm/pubs/rmrs_gtr243.pdf.

Phillips, J.D. 1999. Earth Surface Systems. Blackwell, Oxford.

Pierson, T.D., and J.E. Costa. 1987. A Rheologic Classification of Subaerial Sediment-Water Flows. Geological Society of America, Reviews in Engineering Geology, Vol. VII, p. 1-12.

Pierson, T.C., 2005. Distinguishing between debris flows and floods from field evidence in small watersheds. US Geological Survey Fact Sheet 2004-3142. Retrieved from: https://pubs.usgs.gov/fs/2004/3142/.

Pike, H. 2019. Report: Camp Fire world's costliest natural disaster in 2018, damage cost of $16.5 billion. Retrieved from https://krcrtv.com/news/camp-fire/report-camp-fire-worlds-costliest-natural-disaster-in-2018-damage-cost-of-165-billion.

Rengers, F.K., L.A. McGuire, J.W. Kean, D.M. Staley, and D.E.J. Hobley. 2016. Model simulations of flood and debris flow timing in steep catchments after wildfire. Water Resour. Res., 52. DOI: 10.1002/2015WR018176.

Renschler, C. S. 2003. Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. Hydrol. Proc. 17(5): 1005-1017.

Rickenmann, D. 2016. Methods for the quantitative assessment of channel processes in torrents (steep streams). CRC Press, 150p.

Ries, K.G. 2002. STREAMSTATS: A U.S. Geological Survey Website for Stream Information. Fifth International Conference on Hydroinformatics, Cardiff, UK.

Ries, K.G., P.A. Steeves, J.D. Coles, A.H. Rea, and D.W. Stewart. 2004. StreamStats: A U.S. Geological Survey Web Application for Stream Information. USGS Fact Sheet FS 2004-3115. USGS.

Rio Grande Water Fund. 2015. The Nature Conservancy in New Mexico. The Nature Conservancy, 6 July 2015. https://www.nature.org/en-us/about-us/where-we-work/united-states/new-mexico/stories-innew-mexico/new-mexico-rio-grande-water-fund/

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

Robichaud, P.R., R. Lew, M. Dobre, W.J. Elliot, and E. Brooks. 2019, WEPPCloud Beyond the Horizon. Retrieved from https://www.sedhyd.org/2019/openconf/modules/request.php?module=oc_program&action=view.php&id=247&file=1/247.pdf

Ronstadt, J. A. 2017. Technical Report: Post-wildfire peak discharge prediction methods in northern New Mexico. United States. DOI: 10.2172/1414163.

Rowe, P.B., C.M. Countryman, and H.C. Storey. 1949. Probable peak discharges and erosion rates from southern California watersheds as influenced by fire. U.S. Department of Agriculture, Forest Service, California Forest and Range Experiment Station. Berkeley, CA. Retrieved from https://www.fs.usda.gov/treesearch/pubs/55723.

Rowe, P.B., C.M. Countryman, and H.C. Storey. 1954. Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds. U.S. Department of Agriculture, Forest Service, California Forest and Range Experiment Station. Berkeley, CA.

Santa Barbara County Office of Emergency Management (SBCOEM). 2018. Thomas Fire and 1/9 Debris Flow After-Action Report and Improvement Plan. Retrieved from: https://www.countyofsb.org/asset.c/4550.

Shakesby, R.A. 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Science Reviews 105, p. 71-100.

Shin, S.S. 2010. Response of runoff and erosion with vegetation recovery in differently treated hillslopes after forest fire, Korea. 8th International Symposium on Ecohydraulics. Seoul, Korea, September 2010.

Silver Jackets. 2019. After wildfire: a guide for California communities. 44 pp. http://www.readyforwildfire.org/wp-content/uploads/After-Wildfire-Guide-10JUNE2019_draft_final.pdf.

Smith, R.E., D.C. Goodrich, D.A. Woolhiser, and C.L. Unkrich. 2005. KINEROS – A Kinematic Runoff and Erosion Model. In: V.J. Singh (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, pp. 597-632.

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

Story, M., S. Johnson, B. Stuart, J. Hickenbottom, R. Thatcher, and S. Swartz. 2006. BAER specialist report, hydrology and roads, Derby Fire.

Thomas, M.F. 2001. Landscape sensitivity in time and space – and introduction. Catena 42(2-4), p. 83-98.

Tillery, A.C., M.J. Darr, S.H. Cannon, and J.A., Michael. 2012. Post-wildfire preliminary debris flow hazard assessment for the area burned by the 2011 Las Conchas Fire in North-Central New Mexico. USGS Open-File Report 2012-1188. Reston, VA: U.S. Geological Survey. United States

Forest Service. 2018. Chapter 2520—Watershed Protection and Management, 2523—Emergency Stabilization—Burned Area Emergency Response (BAER). Interim Directive No.: 2520-2018-1. Forest Service Manual, National Headquarters, Washington, D.C.

USACE. 2000. Hydrologic Modeling System HEC-HMS - Technical Reference Manual. U.S. Army Corps of Engineers. Hydrologic Engineering Center, Davis, CA.

Waananen, A.O. and J.R. Crippen. 1977. Magnitude and frequency of floods in California. U.S. Geological Survey. Water Resources Investigation 77-21. Menlo Park, CA.

Wang, J., T.A. Endreny, and J.M. Hassett. 2005. A flexible modeling package for topographically based watershed hydrology. J. Hydrol. 314 (1–4), 78–91.

Wang, J., T.A. Endreny, and D.J. Nowak. 2008. Mechanistic simulation of tree effects in an urban water balance model. J. Am. Water Resour. Assoc. 44, 75–85.

Wang, J., M.A. Stern, V.M. King, C.N. Alpers, N.W.T. Quinn, A.L. Flint, and L.E. Flint. 2020. PFHydro: A New Watershed-Scale Model for Post-Fire Runoff Simulation. Environmental Modelling & Software Vol. 123 (2020), 104555. DOI: 10.1016/j.envsoft.2019.104555.

WEST Consultants, Inc. 2011. Sediment/Debris bulking factors and post-fire hydrology for Ventura County: Final Report. Prepared for Ventura County Watershed Protection District, Ventura, CA.

Wilder, B. and A.M. Kinoshita. 2019. Post-wildfire peak streamflow predictions for small watersheds in southern California, USA. 2019 AGU Meeting, San Francisco, CA. Abstract available at https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/570948.

## 7.1. Case Studies

A number of case studies accompany this toolkit to share how different post-fire goals and questions have been answered using methods, tools, and information found in this toolkit. To a degree, the provided case studies supported the inclusion of the material that makes up this toolkit. Some of these case studies represent efforts undertaken by a single local, State, or Federal agency. Others are reports from an interagency team. Each case study should speak for itself in terms of when (Time Tier/FAF continuity) and why certain actions were undertaken or methods were used. When used in conjunction with this toolkit, these case studies should assist a user in decision-making and assignment completion. They are also useful “refreshers” in the absence of formal training.

1) USGS and CalGS – Thomas Fire, California

2) County of Lake, California – Mendocino Complex Fire

3) USACE – Los Conchas Fire, Bland Canyon, New Mexico

4) USACE – Los Conchas Fire, Cochiti Canyon, New Mexico

5) USACE – Los Conchas Fire, Frijoles Canyon, New Mexico

6) USACE – Los Conchas Fire, Peralta Canyon, New Mexico

7) USFS – First Creek Fire, Washington

8) CALFIRE – Holy Fire WERT Report, California

9) CALFIRE – Thomas Fire WERT Report, California

10) CALFIRE – Valley Fire WERT Report, California

11) CalGS – Inyo Complex Fire, California

12) USACE – Atlas and Nuns Fires, California

13) USACE - Russian River Modeling Methods, California

For more information or assistance accessing these case studies, please call 915-557-5100 or email spk-pao@usace.army.mil.