Racing the rain: A post-wildfire case study in northern NM

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Abstract

In April 2022, a fire started in the Sangre de Cristo mountains of northern New Mexico (NM). By the end of July, almost 342,000 acres had burned making this the largest wildfire in NM history. The wildfire, known as the Hermit's Peak-Calf Canyon (HPCC) Fire, burned the upper watersheds associated with the Canadian and Pecos Rivers. Most of these watersheds have perennial drainages that provide drinking water to smaller communities in northern NM such as Las Vegas and Mora, NM. But the wildfires were only the beginning of the challenges for these communities as convective storms in the summer, known in the southwest as the monsoons, can bring intense rainfall events. Concern over the potential damage from floods and debris that these rainfall events could generate resulted in the charge in early May to model fire affected watersheds to provide insight to emergency management crews on the expected increase in peak flows and the debris yields because of the fires. The goal was to provide this information before the expected start of the monsoon season at the beginning of July.

Modeling was performed using the HEC-HMS software. Since time was of the essence, modeling built upon previous experience with the 2000 Cerro Grande Fire in NM that identified curve number (CN) changes corresponding to burn severity. Four of the five watersheds modeled for the HPCC fire had long-term monitoring of discharge measurements which facilitated the calibration of a pre-fire hydrology. The post-wildfire modeling resulted in larger peak flow estimates by a percent difference ranging from 64% to 1073% compared to the pre-fire estimates, with the largest increases predicted for the more frequent hydrologic events, however a post-fire hydrologic calibration is still needed. Debris yields by subbasin were computed and used to estimate a watershed bulking factor to provide a floodplain delineation more representative of the sediment laden flows. Estimated bulking factors for the modeled watersheds ranged from 1.2 to 2.0.

The monsoon season came earlier than expected in late June, and models were developed for 1,069 square miles of watersheds, and potential event-based floodplains were delineated for almost 387 miles of rivers by mid-July. The effort showed that rapid, high fidelity hydrologic modeling for post-wildfire conditions is possible. The modeling effort also showed limitations

and research needs to improve the reliability of real-time hydrologic and debris yield modeling efforts in the future.

Introduction

The HPCC Fire, located approximately 35 miles northeast of Santa Fe, NM, initiated on April 4, 2022, in the Sangre de Cristo Mountains. As of October 25, 2022, the fire burned 341,735 acres and was 100% contained. On May 4, 2022, the wildfire was declared a major disaster by the President of the United States. The USACE Albuquerque District received a request to aid in response to the ongoing wildfires with the command to provide an estimate of the potential post-fire increase in frequency storms and the corresponding potential inundation extents. Funding was provided mid-May and the expectation was that all modeling would be wrapped up before the monsoons hit this area. This was anticipated to be around the first week in July. The Albuquerque District requested assistance from the Los Angeles and Sacramento Districts because of the short time frame and the amount of work requested. The Hydrologic Engineering Center (HEC) also assisted by providing engineering and modeling support.

Background

Fires increase runoff and peak discharge by both removing vegetation and decreasing infiltration through the soil. Impacts to each depend upon the fire intensity and severity, watershed topography, underlying geology, precipitation frequency, and the amount and type of vegetation burned (Coombs and Melack 2013; Flint et al. 2019). A study by Hallema et al. (2017) compiled data for regional changes in stream flow for watersheds in the years following wildland fires. The study found that post-fire stream flow increased by 266% for a low to moderate burn severity fire in Northern Arizona and by 1,080% in the first year following a moderate to severe burn severity fire in Southern California. Through evaluation of regional differences in stream flow responses, the study concluded that the semi-arid Southwest region has the greatest increase in post-fire peak flows and the most extreme hydrological response to severe wildfire (Hallema et al. 2017).

A study conducted by Livingston et al. (2005) for the 2000 Cerro Grande fire in NM provided estimates of pre- and post-fire CNs and concluded that most subbasins with moderate to severe burn intensities are expected to recover to pre-fire hydrologic conditions within 6 to 10 years, with the most severely burned subbasins expected to recover in 10 to 20 years. This study was near the Los Alamos National Laboratory, which is located approximately 50 miles to the west of the HPCC Fire, providing a relevant and quick means to estimate post-fire precipitation losses in the affected watersheds.

Study Area

The extents of the Hydrologic Unit Code 12 basins for the watersheds affected by the HPCC fire were used to define the study area for this modeling effort. The five watersheds that were modeled are listed in Table 1 and are shown in Figure 1. The map in Figure 1 also shows the burn severity maps for the HPCC fire.

Table **1** includes the percentage of watershed area burned with high, moderate, or low severity or unburned.

Table 1. Burn severity for modeled portions of the watersheds affected by the HPCC fire.

Watershed	% of Area			
	High burn severity	Moderate burn severity	Low burn severity	Unburned
Gallinas Creek	19.0	24.8	30.3	25.9
Upper Mora River	12.3	13.9	19.4	54.4
Sapello River	13.7	20.7	27.2	38.4
Tecolote Creek	5.6	6.7	8.6	79.0
Coyote Creek	3.4	5.7	4.6	86.4

Approach

The HEC Hydrologic Modeling System (HEC-HMS) software (version 4.10 Beta 8) was used for this modeling effort. The model is capable of modeling rainfall runoff and predicting debris yield from subbasins. Three different types of events were modeled in HEC-HMS: 1) pre-fire, clear water 2) post-fire, clear water and 3) post-fire, with debris yield. Debris yield is defined as the total outflow of sediment size clasts (clay to boulders) and organic materials (Gatwood et al. 2010) that is captured by a debris basin. The objective of the hydrologic analysis was to provide an estimate of the magnitude of the flooding and debris yield potential post-wildfire. The peak flows (both clear-water and debris-bulked) were then utilized in hydraulic modeling (AutoRoute) performed by the Engineer Research Development Center (ERDC), Coastal Hydraulics Laboratory (CHL) to develop potential inundation extents for certain annual exceedance probability (AEP) rainfall events.

Watershed Characteristics

The modeled watersheds range in elevation from approximately 6,500 feet at the basin outlets to the upper watersheds ranging from 10,000 feet to 12,600 feet at the highest point. The watersheds are all in the Sangre de Cristo Mountains of northern NM. The Tecolote Creek and Gallinas Creek drain to the Pecos River, while the Sapello River, Upper Mora River, and Coyote Creek drain to the Canadian River. The upper portions of the watersheds were heavily forested and included evergreens such as pines, firs, and spruces, as well as deciduous trees, such as aspen and oak. The lower watersheds were dominated by ponderosa pines, which give way to junipers and pinons as the elevations continue to decrease. The watersheds drain to wide valleys containing a few small developments and some agricultural fields. The lower portions of the watersheds are arid, flat, and contain primarily scattered grasses and shrubs, except along the riparian corridor where cottonwoods and willows receive sufficient moisture to grow. Soils are primarily sandy/silty loams with rock in varying degrees of decomposition. The larger rocks, cobble range and larger, are generally in the higher elevations, with the smaller rocks becoming increasingly more common at the lower elevations. The continuous waterways tend to have an armoring layer that has developed on the bed of the creeks/rivers.

Flooding in the mountain regions can be caused by snowmelt runoff (Waltemeyer 2008) but since the approaching monsoons were not likely to produce snowfall, only rainfall flooding was considered in this assessment. Under the unburned condition, seasonal monsoon events typically do not produce debris flows in these watersheds.

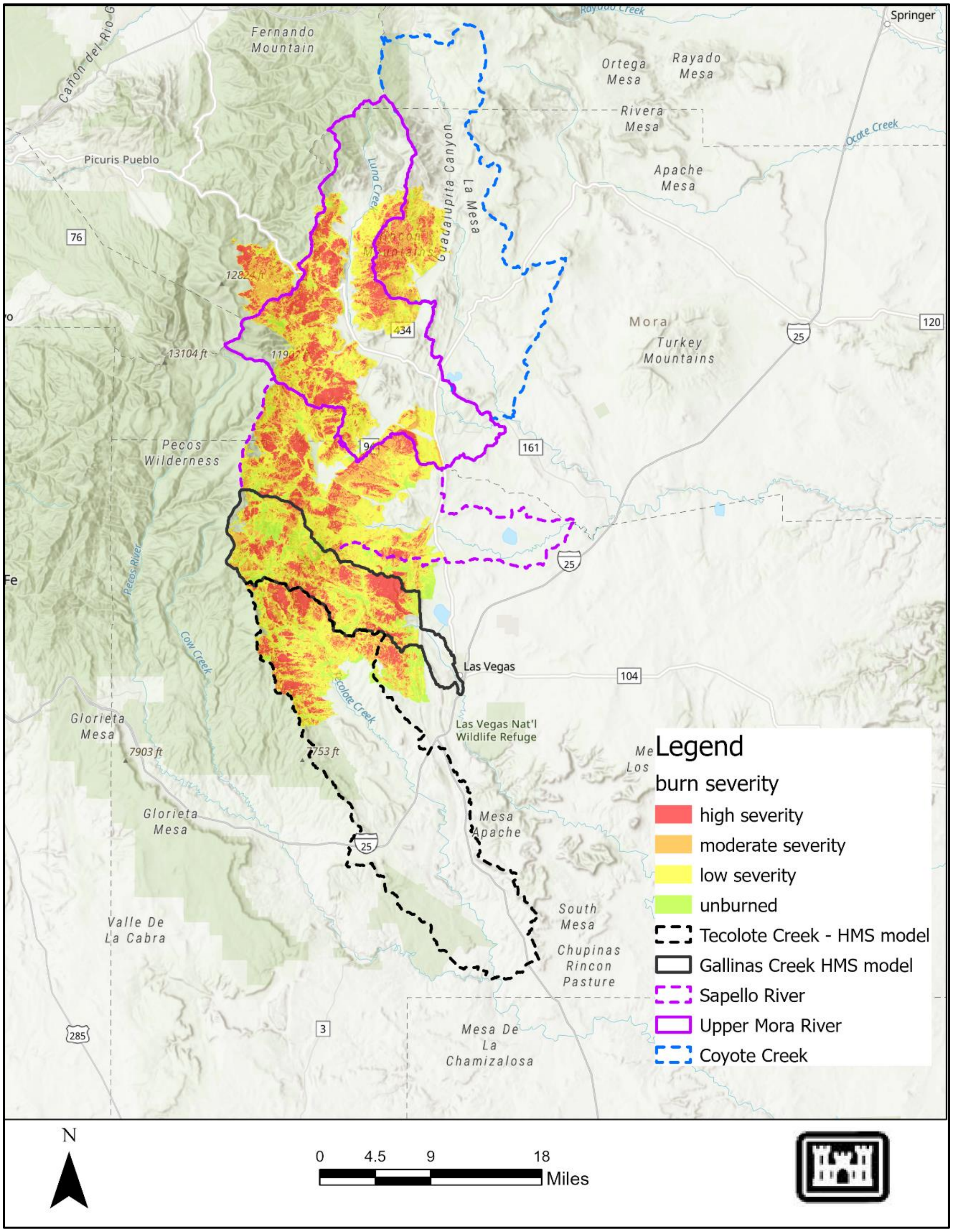

Figure 1. Watershed map, showing the burn severity maps along with the modeled basin outlines. Note any place not showing a burn severity was also unburned. Topographic map was accessed from ESRI archives accessed on 27 November 2022.

Data Collection

The following terrain, precipitation, and stream flow data were collected for the development of the HEC-HMS models.

Terrain

Terrain data was downloaded from the US Geological Survey (USGS) 3D Elevation Program (3DEP) database which produced ten-meter resolution digital elevation models (DEMs) covering the watersheds mentioned previously. This product utilized the best available raster elevation data for this area as of February 2018 (USGS 2021). The spatial reference used for the DEM is Universal Transverse Mercator (UTM) North American Datum of 1983 (NAD83). All elevations are bare earth measurements in units of meters referenced to the North American Vertical Datum of 1988 (NAVD88).

For this analysis, the USGS DEMs covering the study area were reprojected to State Plane New Mexico East with units of feet and a horizontal datum of NAD83. Elevations were converted to units of feet and use a vertical datum of NAVD88. The terrain resolution of 10 meters provided an appropriate level of detail for the hydrologic modeling and reduced the amount of time required for GIS processing and rendering. Terrains were clipped for each modeled watershed and imported into the HEC-HMS software for pre-processing.

Precipitation

For this analysis, precipitation frequency grids from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 were downloaded and used to perform a frequency analysis in HEC-HMS for six different AEP events: 1/2, 1/5, 1/10, 1/25, 1/50, and 1/100. The precipitation grids are specific for the Semiarid Southwest region, the annual maximum series, and a 6-hour duration (NOAA 2017).

Stream Flow

To develop a discharge-frequency relationship for these watersheds, a set of discharge records was assembled. The stream flow records assembled for this study are summarized in Figure 2. All stream gages are operated by the U.S. Geological Survey (USGS). The stream gage with the longest peak flow record was utilized for the watersheds with multiple stream gages. The Sapello River watershed does not contain an active or historic USGS stream gage with a long period of record. Therefore, this watershed was not directly calibrated to observed data. Instead, the flow-frequency curve for the Mora River was scaled by a ratio of the drainage area at USGS Gage ID 0721650 (266 square miles) to the drainage area of the Sapello River (180 square miles) to produce a flow-frequency curve to calibrate the Sapello River model. The watershed characteristics of the Mora and Sapello River are similar making this a reasonable assumption for this modeling effort.

Table 2. Stream flow records for modeled watersheds.

Watershed	Gage Name	USGS Gage ID	Time-Steps Available	Period of Record
Gallinas Creek	Gallinas Creek near Montezuma, NM	08380500	Daily Annual Peaks	1915-2021 1915-2021
Upper Mora	Mora River near Golondrinas, NM	07216500	15-min Daily Annual Peaks	1990-Present 1906-Present 1931-2017
Sapello River[1]	Mora River near Golondrinas, NM	07216500	15-min Daily Annual Peaks	1990-Present 1906-Present 1931-2017
Tecolote Creek	Tecolote Creek at Tecolote, NM	08379300	Annual Peaks	1937-2016
Coyote Creek	Coyote Creek Near Golondrinas, NM	07218000	15-min Daily Annual Peaks	1990-2022 1929-Present 1929-2017

[1]Streamgage data not available. Data from the Mora River gage (USGS Gage ID 07216500) was scaled and used for Sapello River.

Bulletin 17C Analysis: A discharge-frequency analysis was performed to determine the probability of exceedance of discharge values at the stream gages listed in Table 2. Flow-frequency curves were developed using the Bulletin 17C Analysis (England et al. 2019) in the HEC Statistical Software Package (HEC-SSP) (version 2.3) at the selected calibration gages for each watershed. The annual peak flow data for the period of record for each gage was downloaded and used in the Bulletin 17C Analysis.

As described in Bulletin 17C (England et al. 2019), discharge-frequency estimates are improved by weighting the at-site (station) skew with a more robust estimate of regional skew. The regional skew was set to zero and the regional skew mean squared error (MSE) was set to 0.31. These values were selected based on a study by Waltemeyer (2008) that analyzed the magnitude and frequency of peak discharge in NM. The study summarized the findings of previous work which determined that the use of zero for the regional skew improved the fit of observed peak discharge data to the log-Pearson Type III distribution for NM and the Southwestern United States. The study also found that the use of 0.31 as the regional MSE was applicable based on results from a previous investigation in the Southwestern United States.

The flow frequency curve was computed in HEC-SSP resulting in the flow and confidence limits (0.05 and 0.95) for a given percent chance exceedance. The pre-fire peak flows computed for the different AEP events modeled in HEC-HMS were compared to the flow-frequency curve. Input parameters in HEC-HMS were adjusted until the computed peak flow matched the observed flow-frequency curve.

Model Development

The following steps were taken to process data and to define the methods and parameters for the watersheds, modeled as separate basin models, in HEC-HMS.

GIS Processing

The Geographical Information System (GIS) tools within HEC-HMS were used to process the USGS DEM data. The preprocessing sinks and drainage tools were used. For the Mora River, a USGS gage located at the outlet of the basin was used to define a break point within the model. The Sapello River watershed did not contain any active USGS gages, therefore a break point was placed at the outlet of the basin instead. The Gallinas Creek, Tecolote Creek, and Coyote Creek watersheds all had USGS gages located in the interior of the watershed. Break points for these models were defined at the USGS gages and at the outlet locations. The delineate elements tool was used to automatically generate subbasin, reach, and junction elements. The subbasin delineations were reviewed to ensure the drainages of interest were properly captured and manually edited to combine small subbasins where appropriate. The target size for the subbasins was three square miles or less, to meet the maximum size thresholds required for the most restrictive of the post-wildfire debris yield equations within HEC-HMS. This is described in more detail in the Post-Fire Modeling section on Debris Yield. Some of the subbasins are larger than three square miles but were not further divided due to the short timeframe to develop the model and to limit the overall number of subbasins in the model. The five modeled watersheds covered a total area of 1,069 square miles that were modeled within HEC-HMS.

The automatically generated reach elements within HEC-HMS were generally not modified. Reaches less than approximately 500 feet in length were deleted to reduce model instabilities.

Basin Model

The following methods and parameters were selected for this modeling effort to allow for a HEC-HMS model to be developed, calibrated, and adapted for post-fire conditions and debris yield estimates quickly.

Loss: The Soil Conservation Service (SCS) CN loss method was selected due to the limited number of input parameters required and the established methods for adjusting CNs for various burn conditions. While expedient, the SCS CN loss method lumps processes together (e.g., vegetation rainfall interception, soil storage, soil infiltration, etc.) such that some level of calibration is needed to dial in the CNs for a given site. The initial area-weighted CN for each subbasin was estimated using the 2019 National Land Cover Database (NLCD) and the hydrologic soil group from the 2021 Natural Resources Conservation Service's Soil Survey Geographic Database (SSURGO) data sets. Using GeoHMS, a geospatial add-in to ESRI's GIS ArcMap software, an area-weighted CN was computed for each subbasin based on the CN values corresponding to each land cover type and hydrologic soil group. After the initial CN was assigned, all the CNs within a basin were adjusted by a constant factor to calibrate the computed peak flow to the flow-frequency curve, further discussed in the Calibration Section.

The initial abstraction was left blank in HEC-HMS. Leaving the initial abstraction blank will result in HEC-HMS automatically calculating the initial loss as 0.2 times the potential retention, which is calculated from the CN. The percent impervious was set to 0.0% since the CN is considered a lump parameter and land use was accounted for when initial CN values were computed. The percent impervious parameters were not adjusted for post-fire conditions.

Transform: The SCS Unit Hydrograph method was selected for the transform method. The input parameters for the SCS Unit Hydrograph method include the graph type for peak rate factor (PRF) and lag time. The Standard PRF of 484 was used for all subbasins. The lag time for a subbasin is computed as a function of flow length, watershed slope, and maximum potential retention which is a function of the CN. The CN values were varied during calibration, then the lag time was calculated based on the calibrated CN values. Because this is an empirically based method it is best to describe average conditions, only applies to direct surface runoff, and has limitations with regard to frozen soils.

Canopy/Surface: A canopy and surface method were not utilized as it is accounted for in the CN.

Baseflow: A baseflow method was not utilized for this effort due to the limited time available to develop the HEC-HMS model. Most of these watersheds have flow year-round, however the relative magnitude of the baseflow compared to the magnitude of the flood events is small and is not expected to greatly affect the magnitude of the modeled flood events.

Routing: The Muskingum-Cunge routing method was selected as it utilizes physically based input parameters which is advantageous compared to other empirically based methods given the limited post-fire calibration data. The initial type was set to inflow equal to outflow which assumes a steady-state initial condition. The length and slope for each reach was computed in HEC-HMS. The Manning's n values for each reach were estimated based on aerial imagery and the Manning's n values reference table relating land cover type to Manning's n values (USACE 2022b). The auto DX auto DT method was used so the program automatically selects the appropriate space and time intervals to maintain numeric stability. Celerity was selected for the index method, and 5 ft/s was used as the index celerity for all reaches. The index celerity was selected based on the midpoint between base flow and the peak flow, per guidance from the HEC-HMS User's Manual (USACE 2022a). A trapezoid channel shape was used for all reaches. The average bottom width and side slope for each reach was estimated by sampling several cross sections within a reach from the DEM developed for the HEC-HMS model.

Meteorologic Model

A hypothetical storm was used for the meteorological models. The annual maximum precipitation frequency grids from NOAA Atlas 14 were used as the precipitation method. Meteorological models were set up for the 1/2, 1/5, 1/10, 1/25, 1/50, and 1/100 AEP events for the watersheds. A 6-hour storm duration was used for all events to represent the short-duration convective storms expected to occur during the monsoon season. Storm patterns from NOAA Atlas 14 were downloaded and compared during calibration. The storm pattern for the first quartile 70% of duration represents the type of short-duration, high-intensity storms typically observed in the area and produces reasonable results for the different watersheds. Therefore, the first quartile 70% of duration storm pattern was used for all the events and watersheds modeled.

The TP40 area reduction was applied to all basins using the drainage area upstream of the computation point as the storm area input. For the Upper Mora River and Sapello River, the calibration gage is located at the basin outlet, and the same TP40 area reduction was used for all runs (except for the debris yield analysis). For the Gallinas Creek, Tecolote Creek, and Coyote Creek watersheds, the calibration gage is located upstream of the basin outlet. Therefore, separate meteorological models with different TP40 storm areas were created to account for the drainage area upstream of the calibration gage and to account for the drainage area of the entire watershed. An additional meteorological model was developed for the debris yield analyses with the TP40 area reduction removed, further described in the Debris Yield Section.

The frequency analysis computation option in HEC-HMS was used to model the 1/2, 1/5, 1/10, 1/25, 1/50, and 1/100 AEP events in one run for each watershed and pre- and post-fire condition. A frequency analysis was computed at the calibration gage for the pre- and post-fire condition. An additional frequency analysis was computed at the watershed outlet for the post-fire condition to generate peak flow estimates for all the reaches within the watershed for inundation mapping. The simulations were run for a period of one day for the Gallinas Creek and Tecolote Creek watersheds. A simulation period of two days was used for the Upper Mora River, Sapello River and Coyote Creek watersheds. All the watersheds used a time interval of one minute.

Calibration

To calibrate the HEC-HMS models given the limited amount of time, a simplified method of calibrating peak flows to flow-frequency curves was pursued for the pre-fire condition. No information was available at the time of the modeling analysis for a post-wildfire hydrology or debris yield calibration. The HEC-HMS models were calibrated to the peak flow from each frequency event by adjusting the basin loss (CN values), transform parameters (lag time) and PRF, and the storm pattern. The initial CN values were adjusted by a constant factor for the entire basin model until the computed peak flow matched the flow-frequency curve. Increasing the CN values increases the peak flow by decreasing precipitation losses and decreasing lag time, while decreasing the CN values decreased the peak flow by increasing precipitation losses and increasing lag time.

To achieve a better calibration, separate basin models were created for the 1/2, 1/5, 1/10, and 1/25-1/100 AEP events, and the CN values were calibrated independently for each. The CN is a lumped model parameter and the need for separate CN calibrations may reflect a non-linear watershed response to the different frequency events. Using the calibrated CN values, the lag time was computed for each subbasin and applied to the basin models. The CN adjustment was greater for the 1/25-1/100 AEP events compared to the 1/2-1/10 AEP events which resulted in lower calibrated CN values and longer lag times for the 1/25-1/100 AEP basins. A unit hydrograph-based hydrologic model assumes that runoff response is linear; however, runoff response is typically non-linear. As event magnitude increases lag time is expected to decrease. Guidance for inflow design flood development for dams and reservoirs provided in Engineering Regulation (ER) 1110-8-2 (USACE 1991) suggests that inflow unit hydrographs should be peaked by 25 to 50% to account for this non-linear behavior. To account for the expected decrease in lag time, the lag time was reduced by 10% for the 1/25-1/100 AEP basin models for the pre- and post-fire conditions. A 10% reduction in lag time was assumed to be appropriate and conservative since the events modeled are more frequent than the extreme, probable maximum flood (PMF) events used in dam and reservoir studies. Additionally, different PRFs were tested during calibration, and the standard PRF of 484 produced reasonable results and ultimately was selected. Similarly, different storm patterns were tested during calibration. The first quartile 70% of duration storm pattern was ultimately selected as it reflects local conditions and produced reasonable results. Following these steps, the calibrated pre-fire input parameters, methods, and resulting peak flows were established.

Post-Fire Modeling

The calibrated pre-fire input parameters were adjusted to reflect post-fire conditions. First, the post-fire hydrology (peak flow) was estimated by adjusting the CNs. Then, post-fire debris yield for each subbasin was estimated separately and used to calculate a bulking factor for each watershed. Finally, the post-fire peak flows and bulking factors were compiled for a portion of the reaches contained within each watershed to produce inundation maps using a separate hydraulic modeling software (AutoRoute).

Hydrology

A method was devised for modifying CNs (and lag times) to reflect post-fire conditions based on a study conducted by Livingston et al. (2005)of burned watersheds in an adjacent NM watershed and a mesa with steep side slopes in southern Colorado. The watersheds studied by Livingston et al. (2005) have similar climate, terrain, and vegetation to the watersheds burned by the HPCC fire, A relationship was developed by Livingston et al. (2005) that defines a wildfire hydrologic impact (WHI) factor as a function of the percentages of the subbasin area that have been determined to have burn severities of “high” or “moderate”. Burn severity maps were produced for the HPCC fire which cover the burned areas within the modeled watersheds (Figure 1). GIS analysis tools were used to calculate the percentage of subbasin area that was burned with high, moderate, or low severity or was unburned. The percentage of area with high and moderate burn severity was used to identify a WHI factor (low, moderate, severe) for each subbasin based on the relationship developed by Livingston et al. (2005). A second relationship was developed by Livingston et al. (2005) using data from NM and Southwestern Colorado to relate pre- and post-fire CNs (using an initial CN ratio) for each WHI factor. This relationship was used to determine the appropriate initial CN ratio to apply to each subbasin to compute the post-fire CN. An example of this is given in Figure 2.

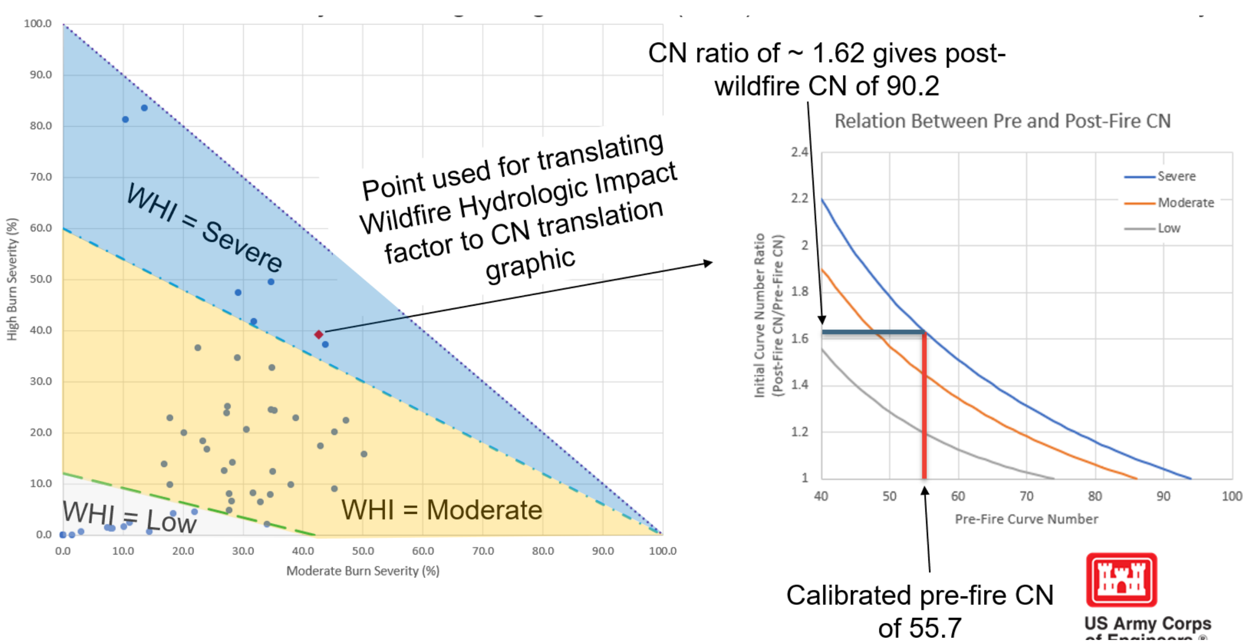

Figure 2. Graphs used to translate burn severity to a post wildfire hydrologic condition. WHI is the Wildfire Hydrologic Index. Blue dots are subbasins for the Gallinas watershed. Red diamond is a point from the Gallinas watershed used to show an example of translating the pre fire CN to the post-fire CN.

Separate basin models and frequency analyses were set up in the HEC-HMS model for the post-fire runs. The computed post-fire CN values were applied to the appropriate basin models and the lag time was calculated based on the post-fire CN values. Like the pre-fire condition, the lag time was reduced by 10% for the 1/25-1/100 AEP basin model to account for the expected decrease in lag time with increased event magnitude.

Debris Yield

There are a variety of methods available within HEC-HMS to evaluate the potential debris yield. Most of these methods are based on the rainfall intensity. The LA Debris Method Equations 2-5 are based on peak runoff flow. Having a debris yield method correlated to the flow is useful since the desire for this modeling effort is to estimate a bulking factor. The bulking factor would be used to multiply the generated clear water post-fire hydrographs for the purpose of floodplain inundation mapping. Bulking factor was calculated as the water and debris volume divided by the water volume.

A comparison was made to other debris methods for some of the watersheds to assess the reasonableness of the LA Debris Method Eq 2-5. The other debris methods are empirical as well but have been more thoroughly tested for watersheds on the order of 3 square miles or less, which is the reason the hydrologic models were set up using this subbasin area threshold. The peak flow rate is more closely related to the total water volume than the rainfall intensity. The debris yield results were reasonable compared to the other equations, so the LA Debris Method Eq 2-5 was selected for this analysis. In evaluations of certain watersheds these resulted in bulking factors within the range of hyperconcentrated flows, 1.2 to 1.7, (MEI 2008), which seems consistent with anecdotal accounts of mud flows and floods following a wildfire condition.

The LA Debris Method Eq 2-5 is a set of regression equations, as shown in Equation 1, that are applicable to subbasins up to 200 square miles (Gatwood et al. 2000). The method is intended for watersheds with steep, mountainous terrain and antecedent conditions that result in saturated soils. The method estimates the volume of debris yield (D_y) using drainage area (A), peak runoff flow (Q), relief ratio (RR), and a fire factor (FF). The RR internally calculated by HEC-HMS was utilized as the RR value by subbasin for implementation of the LA Debris Method Eq 2-5. This was multiplied by 5,280 to convert the units into the desired entry of ft/mile. Within HEC-HMS there is also the ability to specify an Adjustment Transposition Factor (A-T factor) to account for debris yield volume differences between the modeled area and the San Gabriel Mountains, where the data for the original multi-linear regression equations were developed. This factor was set to unity for all the watersheds based on the assumption that the characteristics of the modeled watersheds are similar to the San Gabriel mountains. A user-specified FF was determined for each subbasin based on the fraction of the subbasin area that was burned. Subbasins with 100% burned area (low, moderate, and high) were assigned a fire factor of 6. Unburned subbasins were assigned a fire factor of 3. Partially burned subbasins were estimated based on the formulation in Equation 2 (Gatwood et al. 2000). It should be noted that the FF shown in Equation 2 is for the initial time period immediately after a fire. Gatwood et al. (2000) provide an adjustment to these factors to account for recovery after a wildfire.

$$\log D_y = \alpha \log Q + \beta \log RR + \gamma \log A + \delta FF \quad (1)$$

$$FF = 6A' + 3B \quad (2)$$

Where α, β, γ, and δ are numerical regression parameters that are specific to a watershed size range, A' is the fraction of the subbasin that is burned, B is the fraction of the subbasin that is unburned, and the other parameters are as defined in the text.

HEC-HMS also provides the ability to define a flow threshold below which debris yield will not be calculated and to modify the shape of the debris yield curve relative to the hydrograph. The flowrate threshold was set to the HEC-HMS default value. The shape of the debris hydrograph was set to unity, so it mirrors the water hydrograph. Finally, HEC-HMS provides for the ability to parse the estimated debris volume in terms of sediment size classes. For this evaluation a single gradation curve was entered for each watershed since only the overall volume was utilized for the bulking calculations.

Separate basin models were copied from the post-fire hydrology basin models in the HEC-HMS model for the debris yield runs. Only the subbasin debris yield functionality in HEC-HMS was used. Debris routing through the reaches was not incorporated due to limitations in the current hyperconcentrated and debris routing methods and lack of data to calibrate. Therefore, the reach elements were deleted from the basin models and debris yield was computed separately for each subbasin. The LA Debris Method Eq 2-5 was selected as the erosion method and the associated parameters, previously discussed, were assigned to each subbasin. Simulation runs were set up and run for each AEP event with the debris yield basin models and corresponding meteorologic models. The TP40 area reduction was removed from the meteorological models for the debris yield analysis because the subbasins were modeled independently with the reaches removed. This increases the debris volume relative to the water volume, resulting in a conservative bulking factor. This was done since there is the potential for the reaches to generate additional debris yield through reach elements during an event.

The resulting debris yield from each subbasin was summed and used to calculate bulking factors for each AEP event. The debris yield in HEC-HMS is calculated and the output is presented based on the weight of the debris in units of short tons. The user entered unit weight of the soil was used therefore to convert the debris weight to volume with short tons converted to pounds and cubit feet converted to cubic meters. Since the total debris load (and not soil types) was used, the unit weights do not need to represent the actual unit weight of the soil types present in the watershed. A single bulking factor was calculated for each watershed by summing the total debris and water volume for each event at the outlet. The bulking factor represents a conservative, average condition for the watershed and is not specific to the debris yield and runoff for a given subbasin.

Inundation Mapping

A portion of the reaches within each of the watersheds were identified as areas of interest for post-fire inundation mapping. Inundation maps were developed by the USACE ERDC CHL using the AutoRoute hydraulic modeling software. The post-fire peak flows computed in HEC-HMS corresponding were provided to ERDC as the input parameters for AutoRoute. For AutoRoute reaches with more than one HMS element contributing flow to it (i.e., flow in a reach and local runoff from the subbasin), the peak flow from each element was added together. The timing of the peak flows was not preserved by adding the hydrographs. Instead, the conservative assumption was made to add the peak flows directly to produce a composite floodplain with the maximum inundation extents. To account for the increase in volume due to the debris yield, a bulking factor was applied to the peak flows in AutoRoute. A single bulking factor was estimated for each watershed, described in the Debris Yield Section, and was applied to all the reaches within that watershed for a given event.

Results

A graphical example of the pre-fire and post-fire peak flows for the various AEP events is shown in Figure 3. The increase between the pre- and post-fire peak flows and the calculated bulking factors are presented in
Table **3** for the five modeled watersheds affected by the HPCC fire.

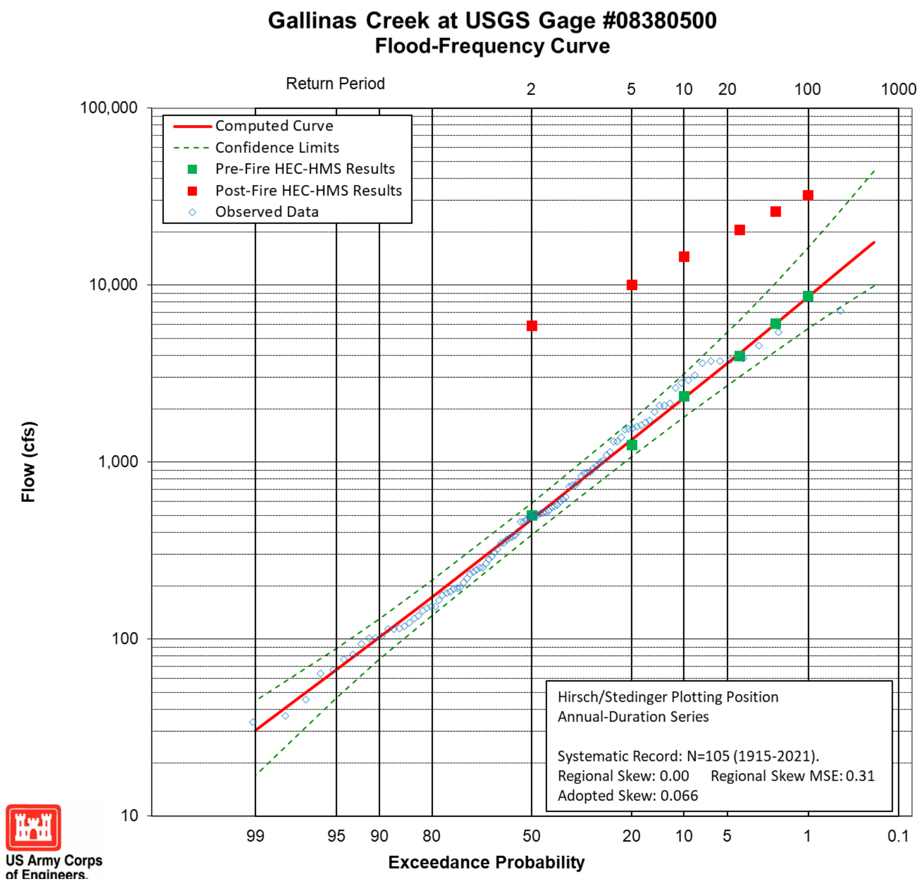

Figure 3. Flow frequency analysis for Gallinas Creek showing the pre-fire calibration (green points) and the calculated post-fire (red points) AEP event peak flows

Table 3. Post-wildfire peak flow increases, and estimated debris yield bulking factors for watersheds affected by the HPCC fire.

Watershed	Range of Peak Flow increase from pre-fire to post-fire (%)	Bulking Factor ranges
Gallinas Creek at I-25 Crossing	270 - 1070	1.7 – 1.9
Upper Mora River near Golondrinas, NM	240 - 580	1.6 – 1.8
Sapello River ~ 6 miles upstream of I-25	350 - 790	1.5 – 1.7
Tecolote Creek at Tecolotito, NM	87 - 470	1.3 – 1.6
Coyote Creek at confluence with Rio Mora	64 - 200	1.6 – 2.0

Conclusions

The HPCC Fire, the largest wildfire recorded to date in NM, triggered a collaboration to minimize the potential flooding and damage to local communities affected by the fire. In early May, the Albuquerque District was tasked to provide estimates of the potential flooding and debris yield magnitudes prior to the onset of the summer monsoon storms. Aided by the Los Angeles and Sacramento Districts, as well as the Hydrologic Engineering Center, five HEC-HMS models were developed by the end of June with information about the peak flow increases and inundation extents for certain AEP events being distributed by mid-July. While not quite beating the onset of the monsoons, which arrived earlier than expected in the last week of June, rapid, high-fidelity hydrologic models were developed in advance of the bulk of the monsoon season.

The SCS CN and SCS Unit Hydrograph methods were used to develop and calibrate the HEC-HMS models to flow-frequency curves for the watersheds within a limited timeframe. Pre-fire peak flows were calibrated, then CNs were modified to reflect post-fire conditions and estimate post-fire peak flows. The results of this assessment are within the range of values found in previous studies (Hallema et al. 2017). While the estimated increase in post-fire peak flows for the modeled watersheds is extreme, the Hallema et al. (2017) study also concluded that the semi-arid Southwest region has the greatest increase in post-fire peak flows and the most extreme hydrological response to severe wildfire compared to other regions within the United States. Therefore, the results of this assessment provide a reasonable estimate of post-fire peak flows that have the potential to occur in the immediate future in the watersheds affected by the HPCC fire.

The Coyote and Tecolote Creek percent increase of the peak flow was smaller because of the small burn percentage of these watersheds compared to the other watersheds. Due to the lower peak flows and overall lower flow volume for the Coyote Creek watershed, the bulking factors were higher than the other watersheds including the Upper Mora River which has a comparable drainage area but larger percentage of burned area. The bulking factors were expected to be lower for watersheds with smaller percentages of burned area. The Coyote Creek watershed provides an example of a potential limitation of the LA Debris Method Eq 2-5 to accurately represent partially burned watersheds and highlights the need to calibrate post-fire parameters as data becomes available.

While the goal of the modeling was to provide a potential flooding risk for emergency management crews around the affected burn area, if more time was available, it would be desirable to calibrate the pre- and post-fire peak flows to a select number of events. In this manner, the timing and shape of the hydrographs are calibrated, along with the peak magnitude. Inclusion of a baseflow, while not deemed critical for the modeling effort, would add confidence to the overall model. The post-fire modeling effort employed does provide the means to moderate the effects of the fire over time and could be used in subsequent years to forecast peak flows as the vegetation returns within the watershed. Finally, there appeared to be flow diversion channels or other flow conveyance structures in the watershed terrain but were not directly modeled in the HEC-HMS model. If these structures are expected to affect peak flows, by being clogged by debris for example, then they should be added or accounted for in the model.

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