NRCS POST-FIRE HYDROLOGIC MODELING IN NEW MEXICO 2012

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Abstract Wildfire can ravage enormous areas of the landscape and initiate extensive efforts among many agencies to combat the active event. Post-fire consequences also require attention, as the sudden watershed changes wrought by fire leave communities vulnerable to much larger floods, sedimentation, and debris flow. The Natural Resources Conservation Service (NRCS) in New Mexico played an important role both during and after large wildfires in the summer of 2012. Rapid application of the Emergency Watershed Protection (EWP) program funded several temporary USGS precipitation collection stations in the burned watersheds to help forewarn communities of possible flooding. Forest Service Burned Area Emergency Response (BAER) teams provided rapid assessment of the expected hydrologic consequences of the fire. NRCS followed up with detailed watershed modeling of Whitewater Creek, so that expected flood peaks and sedimentation could be quantified. Subsequent extreme storm events occurred in September 2013 in Whitewater Creek, New Mexico, and in Colorado's Front Range, the latter making national news. Development of the NRCS post-fire hydrologic analysis is detailed herein, with output including model performance of the 2013 observed event.

INTRODUCTION

Lightning sparked several outbreaks of wildfire in May 2012 that joined to became the largest in New Mexico recorded history. Lack of road access and the steep terrain of the Gila Wilderness Area hampered containment efforts, allowing the individual fires to grow rapidly. By the end of May, they had become one large wildfire known as the Whitewater-Baldy Complex.

The rugged landscape was not the only reason these fires escaped control. The watershed had already been under extreme drought conditions, with very little snowfall during the two previous winters. Air temperatures at the time of the outbreak were well above average, and high winds contributed to the merging of the fires. In early June, the Whitewater-Baldy Complex was only about 18 percent contained. By mid-June, containment increased to 56%. For about three months, the wildfire burned Ponderosa, Pinon/Juniper, and mixed conifer forests with relatively low burn temperatures. Rainfall in mid-July finally helped fire fighters gain momentum, with 95% containment attained in late July.

The wildfire burned about 465 square miles. The USDA Forest Service estimated final burn severity for the area within the fire perimeter to be 14 percent high, 12 percent moderate, 55 percent low or unburned, and 20 percent unknown (due to inadequate satellite imagery). Figure 1 shows the general location of the wildfire.

The NRCS Emergency Watershed Protection (EWP) program funded the installation of monitoring gages in the Whitewater-Baldy Complex burn area, to provide early warning to downstream communities of flood potential. The intensity of the wildfire and its large area prompted the Forest Service, in cooperation with the United States Geological Survey (USGS),

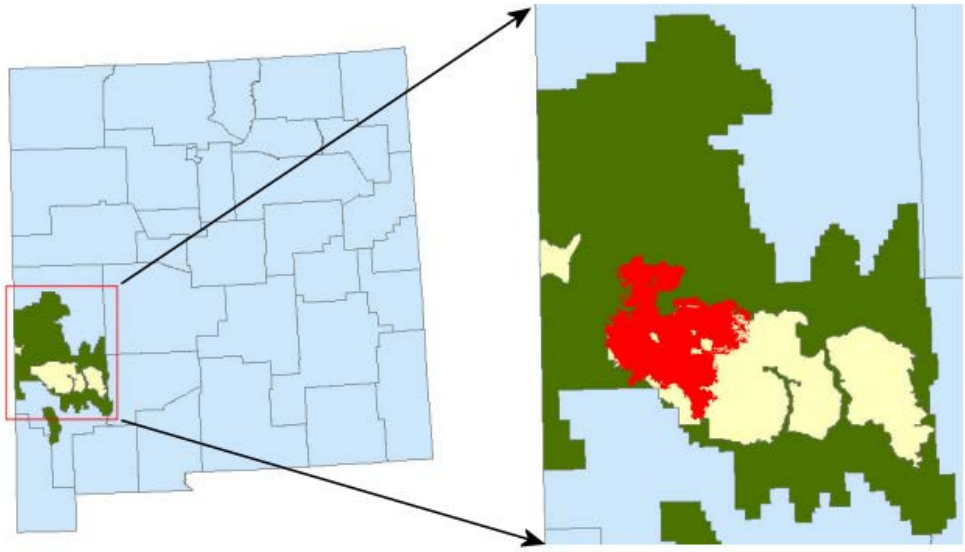

Figure 1 SW New Mexico, Gila National Forest (green), Gila Wilderness area (yellow), Whitewater-Baldy Complex wildfire (red).

to seek EWP funding from NRCS. The NRCS New Mexico State office worked with the New Mexico Department of Homeland Security and Emergency Management, which acted as the EWP local sponsor. USGS installed a streamflow gage on Whitewater Creek, near the Catwalk Recreational Area (figure 2). That station also received a precipitation gage. The location of the existing NRCS snow telemetry (SNOTEL) site is also shown in figure 2, along with additional precipitation gages installed by USGS using EWP.

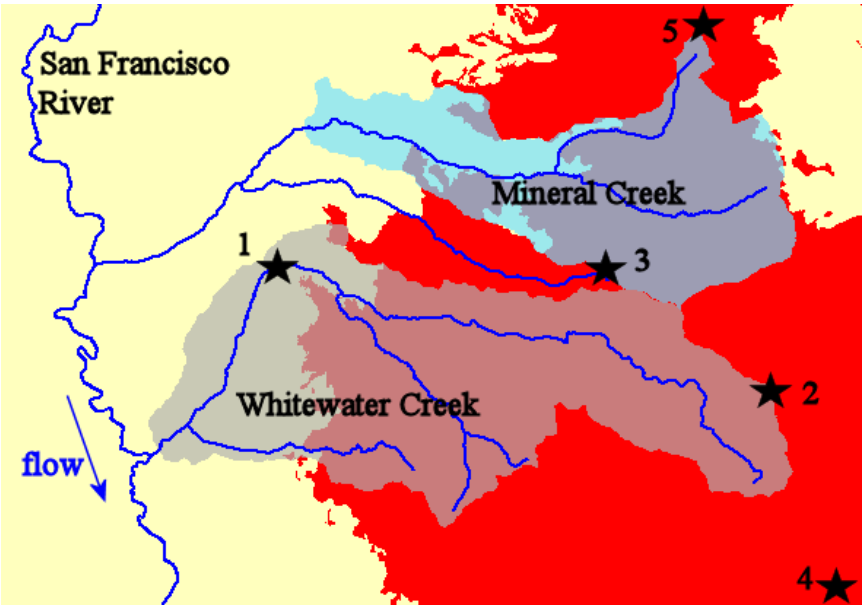

Figure 2 Gages in the burn area (red): Silver Creek Divide SNOTEL site (3), streamflow and precipitation at Catwalk (1), precipitation at Hummingbird Saddle (2), Mogollon Baldy Lookout (4), and Bear Wallow Lookout (5).

NRCS also performed a hydrologic analysis to assess flood potential for the community of Glenwood. In recent years New Mexico residents experienced flash flooding after wildfire. Hypothetical floods examined were pre-fire, post-fire immediately after the burn, and post-fire, one year later. Data from the newly installed precipitation and streamflow gages were used to verify that the hydrologic model produced reasonable results.

HYDROLOGIC MODELING DETAILS

After selecting a software application for watershed modeling, the hydrologist has key decisions to make about how to represent the landscape. These are an attempt to guide the model in partitioning precipitation between infiltration (and other losses) and runoff, and secondly, transforming remote runoff to an outlet hydrograph. The NRCS hydrologic model WinTR-20 employs the curve number runoff method, with curve numbers (generally between 30 and 99) that affect runoff volume (USDA-NRCS, 2004). Curve numbers are a subarea index, which includes losses to transpiration and ponding. Within the US Army Corps of Engineers model, HEC-HMS (USACE-HEC, 2013), these losses can be specified separately. The model provides several infiltration options, including curve numbers, and the Green-Ampt method. The latter is an attempt to model the physical infiltration process using soil characteristics such as hydraulic conductivity.

The draft NRCS National Technical Note Hydrologic Analysis of Post-Wildfire Conditions (USDA-NRCS, 2014), currently under review, provides a comprehensive guide to hydrologic modeling of post-wildfire conditions. The hydrologic model of Whitewater Creek, New Mexico, discussed in this paper is included in the technical note as a case study. The hydrologic modeling choices selected for Whitewater Creek were the HEC-HMS model, with Green-Ampt infiltration, and a user-specified unit hydrograph for runoff transformation.

Issues Particular to Post-Wildfire Modeling

The hydrologist has several challenges with burned watersheds. Adequate historical data records generally do not exist. The often remote and mountainous watersheds may never have been gaged or studied for rainfall-runoff behavior, which would establish indices such as curve numbers or peaking factors for synthetic unit hydrographs (UHs). Even if they were gaged, the gages would have to survive wildfire events to be available for monitoring the sudden watershed changes caused by the fire. New gages can be rapidly installed after an event, such as occurred for the Whitewater-Baldy Complex fire, but rarely is this action taken, and such data cannot provide insight into pre-fire runoff behavior.

Research literature to date does not provide post-wildfire modeling guidance that would remove much hydrologic judgement from the effort. The NRCS technical note (USDA-NRCS, 2014) gives several tables of post-wildfire runoff curve numbers (CNs) that have been compiled from previous hydrologic modeling efforts. Generally, these CNs have been selected using hydrologic judgement rather than being data-derived. One study of ten Appalachian forested watersheds, that did use data, found measured CNs varied significantly from published suggested values (Tedela, et al., 2012). The study also found very wide confidence limits for the measured values. One watershed, with a measured mean CN of 57, had 95 percent confidence interval of 32 to 83.

Other data-driven studies also found inability to achieve a stable CN value (Hawkins, 1993, and Springer and Hawkins, 2005).

Another source of uncertainty in hydrologic modeling of mountain watershed is in the use of synthetic unit hydrographs that include a user-specified peaking factor. The unit hydrograph transformation algorithm in WinTR-20 has a default peaking factor which applies to U.S. watersheds of average flow slopes and landscape storage effects. Mountain watersheds tend to have much steeper slopes and fewer storage effects than average. A hydrologist using WinTR-20 has the option to change this peaking factor, but the program does not make it obvious when it should be changed, and retaining the default is the likely practice, even for mountain watersheds. When using HEC-HMS the hydrologist cannot select an SCS peaking factor, but has only two hydrograph shape options: standard (the default peaking factor) and "Delmarva", a hydrograph shape developed by NRCS for the Delaware, Maryland, and Virginia peninsula, and often used for Eastern U.S. coastal watersheds. (A larger range of optional peak factors is planned for HEC-HMS version 4.1.)

To escape the need for a peak factor estimate, the hydrologist may consider other synthetic unit hydrograph options available in HEC-HMS. But similar user-entered factors are also required with those synthetic UH choices. For example, the Clark synthetic UH transform requires the user to specify a "storage coefficient" which, according to the user manual (USACE-HEC, 2013), may be determined from regional studies. The Snyder synthetic UH transform requires a "peaking coefficient" obtained, according to the user manual, "…using the best judgement of the user, or possibly from locally-derived relationships to watershed physical features."

The HEC-HMS model does offer a UH transform method that may get around the peaking factor issue: the user-derived UH. Of course, measuring the UH applicable to any given watershed requires data, but a synthetic UH may be derived if the user can determine an adequate time-area histogram of the watershed. Even without rainfall and runoff data, geographic information systems (GIS) may give the hydrologist the best handle on the shape of the mountain watershed hydrograph. Good resolution digital elevation models (DEMs) enable the land slope to be defined. More and more pertinent digital geographic data is becoming available, such as soil type, land cover, vegetation, and even burn extents and severities. The ArcGIS raster calculator (ESRI, 2010) enables the modeler to estimate flow velocities for overland flow slopes, collector channels, and major streams, and then travel times from any point in a watershed. This option was used for the Whitewater Creek study.

Soil hydrophobicity may be the most difficult effect of wildfire to model, and thereby the greatest source of uncertainty. The NRCS technical note discusses the phenomenon extensively, with numerous references, such as DeBano (2000) and Huffman, et al. (2001). Wildfire can result in soils becoming water repellent, but the pertinent landscape aspects vary widely and are not very quantifiable. Certain vegetation types, when burned, provide gaseous hydrocarbons that condense in cooler soil layers. Soil texture plays a role, in that coarse-grained soil is more susceptible than finer-grained soil.

Soil burn severity may have an important role in the strength of water repellency at a given location and the geographic extent. However, even as water repellency is created, the depth into

the soil of the top of the hydrophobic layer varies, and the thickness of that layer varies. Along with those unknowns comes variability in the time after a wildfire event that the hydrophobic characteristics persist.

The hydrologic modeler has a few reasonable options for estimating hydrophobic extent, but the uncertainty thrown into the runoff model is large and unquantifiable. For example, using GIS, a layer for soil burn severity could be combined with soil and vegetation layers to estimate where hydrophobic soil may exist, but the correlation may not be very good. Uncertainty also remains about whether hydrophobic soil restricts infiltration completely or only partially, and whether a sub-basin should be considered 100 percent hydrophobic or whether some lower fraction should be used. Relating to post-fire sedimentation, more erosion would tend to result from areas where loose soil exists above the hydrophobic layer, and rainfall on the unprotected soil can perch on the hydrophobic layer and run off similarly to a parking lot pavement. Again, the volume of such erosion would be highly uncertain.

As a result of all this uncertainty, the modeler must incorporate estimates about hydrologic conditions which cannot be verified. These estimates, along with the scarcity of gages, contribute to the fact that the hydrologic model cannot be calibrated. Model results will be reasonable, but the modeler should document areas of unknown variability. If post-wildfire data stations exist, such as in Whitewater Creek, the data can be used to adjust model input and examine the difference between modeled and measured runoff. However the geographic extent of the station network would generally remain too sparse for true model calibration.

Whitewater Creek Hydrologic Model

The total watershed area of Whitewater Creek upstream of the San Francisco River is 54.5 square miles. Upstream of the new Catwalk streamgage (figure 3) the drainage area is 36.2 square miles. Figure 3 shows how the basin was sub-divided for the hydrologic model. The inset of figure 3 is a single upstream sub-basin, shown in figure 4. Much of this discussion will focus on this sub-basin, as every other sub-basin is modeled similarly.

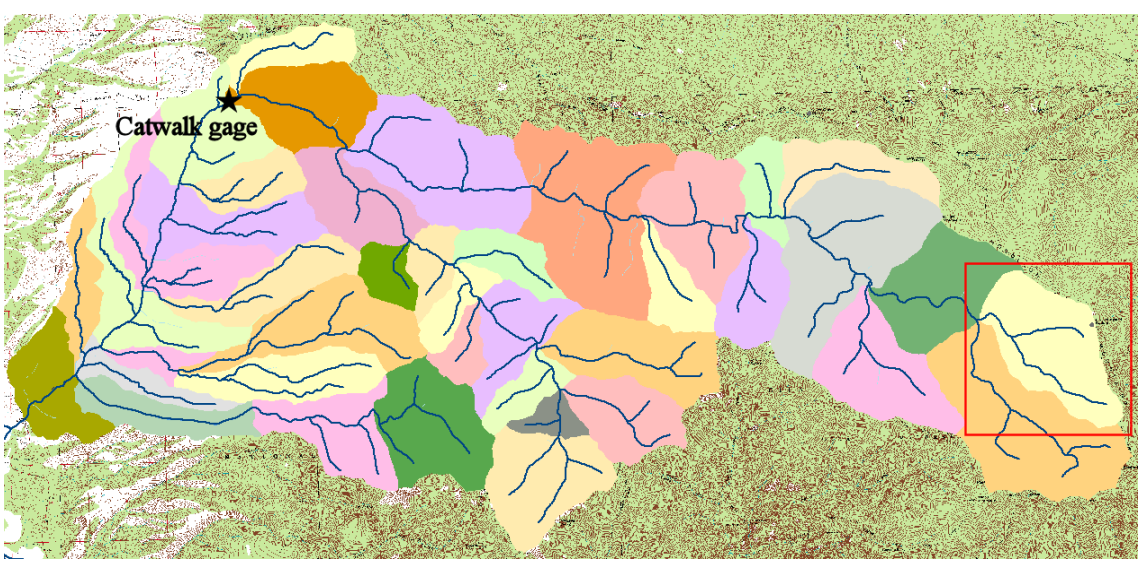

Figure 3 Whitewater Creek sub-areas, with inset of Baldy Fork (see figure 5).

For Green-Ampt infiltration, HEC-HMS requires soil data for initial moisture content, saturated content, matric suction, and hydraulic conductivity. Being within the Gila Wilderness, spatially distributed soil data are not available. However, a soil survey for part of Catron County outside the wilderness is available (USDA-SCS, 1985). The document shows that a typical soil of the area is the Tolman Series, for which the texture of the top two inches is described as cobbly loam, with permeability ranging between 0.6 to 2 inches per hour. For the entire watershed, the Green-Ampt parameters were estimated based on this soil type, with reference to the technical note table of hydraulic characteristics by soil texture. The assumed soil texture was loamy sand with porosity of 0.42 cubic inches of pore space per cubic inch of soil. Initial moisture content was assumed to be near field capacity, or 20 percent of the porosity. Wetting front suction was estimated at 4.33 inches and hydraulic conductivity 0.86 inches per hour.

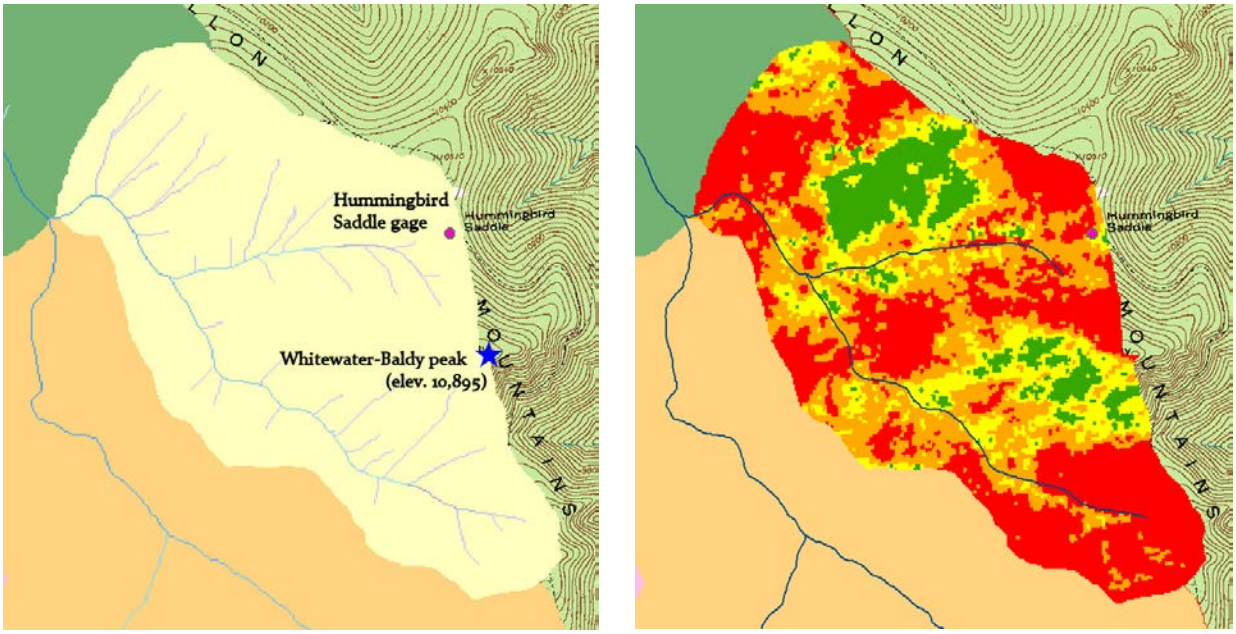

Figure 4 Baldy Fork sub-basin with burn severity raster on the right, (red = high, orange = medium, yellow = low, green= no burn).

Transformation of downstream runoff was accomplished using a unit hydrograph for each sub-basin derived from a GIS-estimated time-area histogram. Flow velocity for each ten-meter DEM cell was determined using Manning's equation, with a partitioning of cells into the catagories of overland flow, shallow-concentrated flow, or channel flow. The category was based on distance from the headwater ridge of each flowline. NRCS guidance (USDA-NRCS, 2010) suggests that overland flow will extend only up to 100 feet before transitioning to shallow-concentrated flow, which may extend another 1000 feet before becoming channelized. Separate Mannings roughness values are assumed for the different flow categories and for different types of vegetation or soil for each cell. In addition, burn severity was taken into account. (See figure 4).

Figure 5 shows the time band raster for Baldy Fork, derived using the ArcGIS raster calculator. Further details of the time-area histogram derivation is provided in USDA-NRCS (2014). The

time band table in figure 5 shows the number of cells that drain to the outlet in each 5-minute band. These data are copied to a spreadsheet and a time-area histogram created. Further spreadsheet manipulations result in the unit hydrograph shown in figure 6. Note that varying the conditions for travel time rasters results in separate unit hydrographs for pre-fire conditions, post-fire conditions immediately after the fire, and conditions after one year of healing.

The NOAA National Weather Service Precipitation Frequency Data Server (NOAA, 2013) was recently updated for New Mexico. Due to the flashy character of Southwest U.S. storms, a six-hour duration was selected for analysis, with rainfall amounts in table 1.

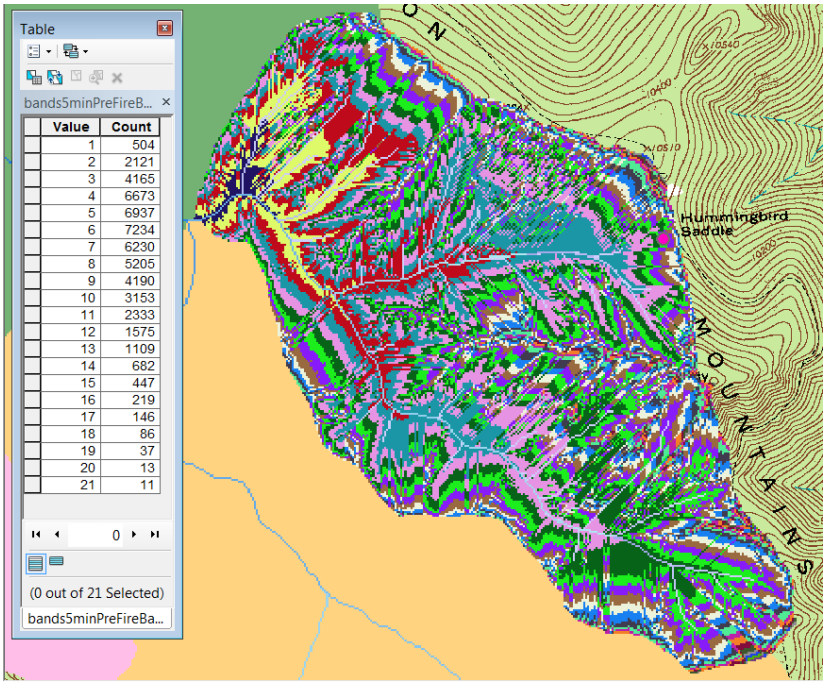

Figure 5 Twenty-one 5-minute travel time bands for Baldy Fork, with inset attribute table.

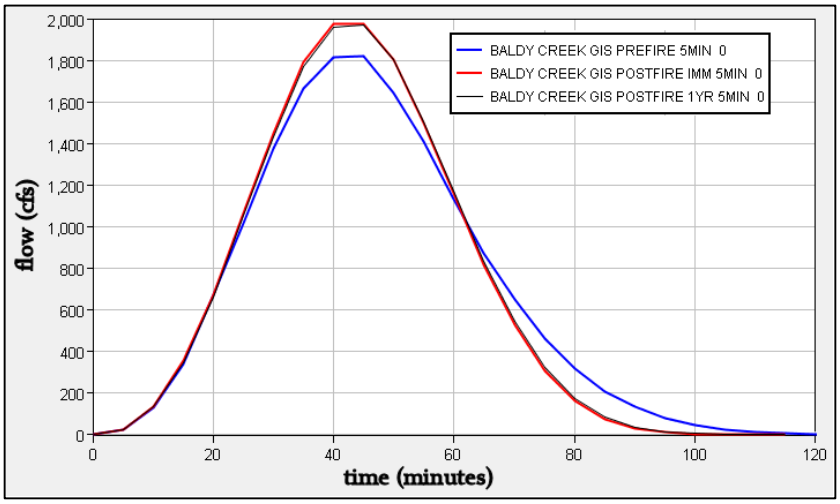

Figure 6 Synthetic GIS-derived unit hydrographs for Baldy Fork.

Table 1 Whitewater Creek watershed 6-hour duration storm totals

watershed area	precipitation		
	2-year (inches)	25-year (inches)	100-year (inches)
upper Whitewater	1.54	2.73	3.49
SF Whitewater	1.42	2.49	3.19
lower Whitewater	1.20	2.12	2.73

These rainfall amounts were distributed in time using a New Mexico variation of the standard NRCS Type II storm distribution. (The New Mexico variant results in a slightly higher peak than the NRCS Type II and causes the peak to occur earlier in the duration.) In addition, an areal reduction factor (ARF) was applied to the rainfall values of Table 1, based on the graph in figure 7, from Osborne, Lane, and Myers (1980). The Walnut Creek Experimental Watershed of figure 7 is near Tuscon Arizona, about 180 miles from Whitewater Creek, but in the same hydrographic region. Similar areal reduction is expected. The marked drop off of precipitation with distance, shown in figure 7, indicates that typical storms in the US Southwest are not large enough to cover the entire watershed of a size like Whitewater Creek. Typical storms may be 10 to 12 km in diameter, while Whitewater Creek is about 22 km wide, east to west. The storm centerings for the Whitewater Creek model are shown in figure 8, with locations selected which result in the largest runoff effect.

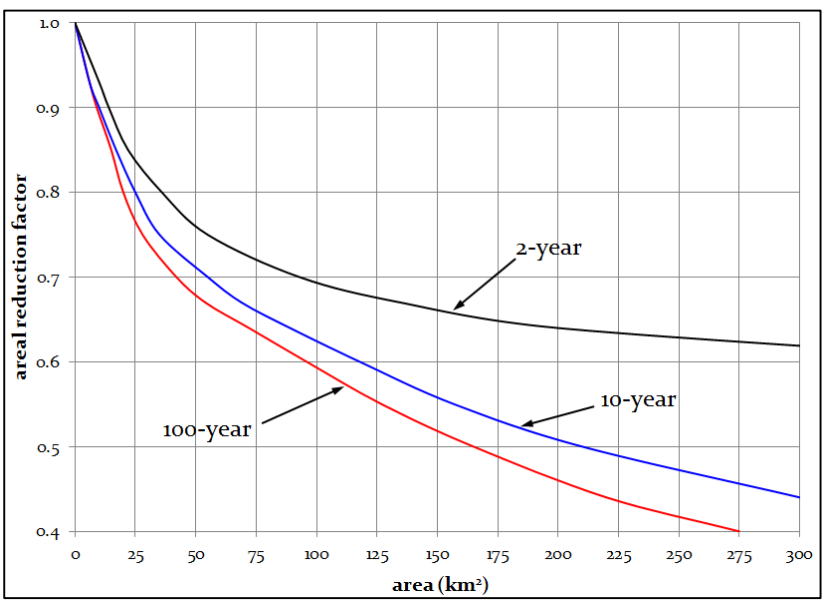

Figure 7 Areal reduction factors developed for 6-hour duration storms at Walnut Gulch AZ Experimental Watershed (modified from Osborn, Lane, and Myers 1980)

This analysis did not attempt to model sedimentation, but relied on a USGS report specifically concerning the Whitewater Baldy Complex wildfire (Tillery, Matherne, and Verdin, 2012) that estimated high probabilities in Whitewater Creek of debris flows from 30-minute duration

rainfall events for recurrence intervals of 2-year, 10-year, and 25-year. The report provides a map of Whitewater Creek sub-basins and their estimated propensity to generate sediment due to the wildfire. This information was used in this case study to bulk the modeled clear flow hydrographs, depending on their origin.

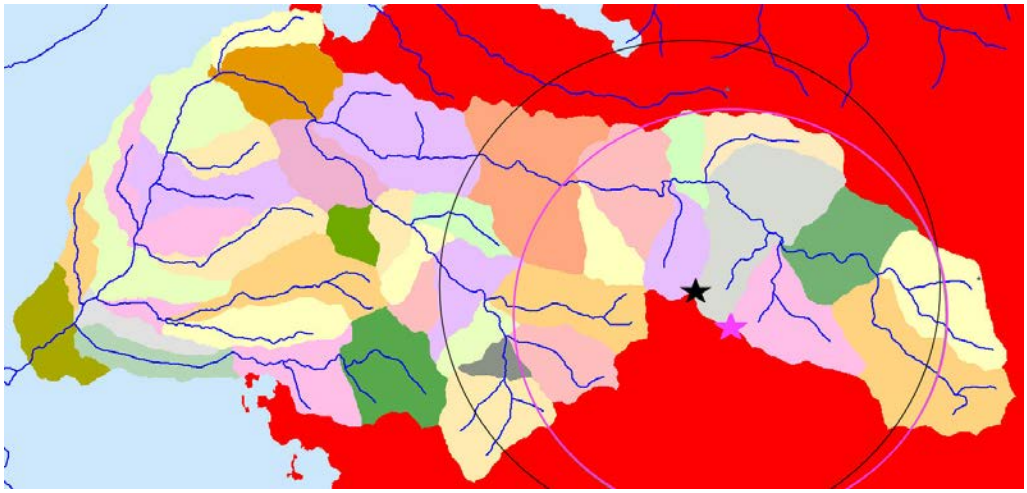

Figure 8 Storm centerings: UpperGrouse, 6 km radius (black), UpperLipsey, 5 km radius (pink)

MODEL RESULTS AND DISCUSSION

The HEC-HMS model can produce hydrographs for any of the sub-basin outlets of figure 3, but only the USGS gage at Catwalk (figure 2, gage 1) and the creek outlet to the San Francisco River (near Glenwood) are shown here. Three watershed scenarios were examined, pre-fire, immediately post-fire, and post-fire after one year of healing. Table 2 shows that varying storm center location and storm size (5- or 6-km radius) does not produce widely different results. Figure 9 shows the 100-year hydrograph at Glenwood for the 6-km radius storm.

Table 2 Model output: hydrograph peaks in cfs with areal reduction centerings from Figure 9.

storm	location	Grouse centering (6km radius)			Lipsey centering (5km radius)		
		pre-fire	post-fire (immed.)	post-fire (one year)	pre-fire	post-fire (immed.)	post-fire (one year)
100-yr	gage	10149	15734	14623	9246	15052	13500
100-yr	Glenwood	8776	14391	13245	7916	13899	12431
25-yr	gage	4384	9703	8696	4589	8654	7765
25-yr	Glenwood	3854	8713	7674	3934	7919	7060
2-yr	gage	31	4346	2878	56	3723	2405
2-yr	Glenwood	31	4121	2734	46	3555	2308

The observed event of 14-15 September, 2013, was modeled using the post-fire after one year scenario. The event magnitude was more rare than a 1,000-year recurrence, as shown in table 3. Some evidence of storm areal extent is provided by the fact that the Hummingbird Saddle gage during this event received minimal precipitation. The storm seems to have occurred closer to the

gage. Between 9 pm and midnight, while the Catwalk gage was recording 6.10 inches of rainfall, the Hummingbird Saddle gage received zero. For the three hours after midnight, rainfall at Catwalk dropped off considerably (0.75 inches, total) and Hummingbird Saddle recorded a similar total (0.93 inches). The Silver Creek Divide SNOTEL site (figure 2, gage 3) recorded precipitation of about two inches for that 24-hour period. (The SNOTEL precipitation gage is a cumulative collection cylinder, with historical records of daily observations.)

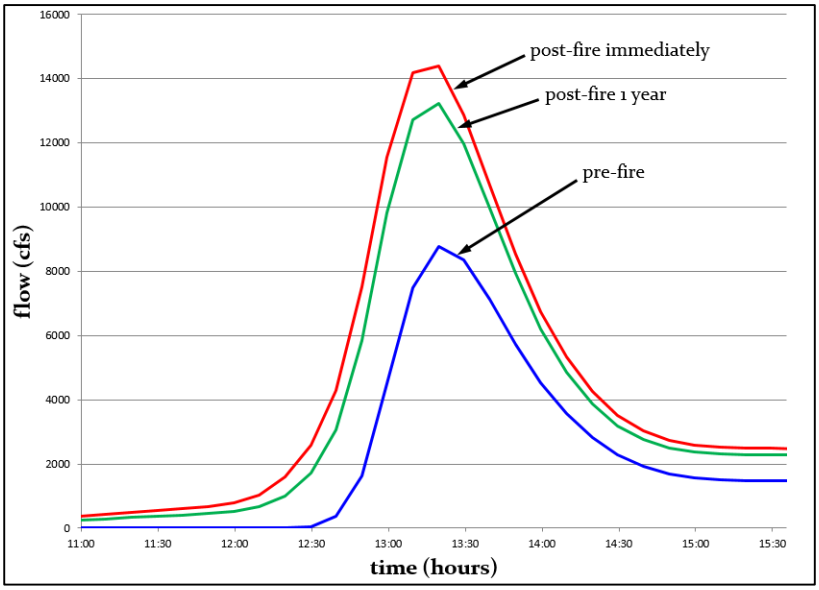

Figure 9 Model results, 100-year hydrographs at Glenwood for 6km radius storm.

Table 3 Observed storm event measured at Catwalk gage (blue) with NOAA precip-frequency.

storm centering at SF Whitewater confluence (rainfall in inches)							
	recurrence-->						
duration	50-year	100-year	200-year	500-year	1000-year	gage	14-15 Sep
1-hour	1.83	2.04	2.24	2.5	2.71	**3.01**	9-10 pm
2-hour	2.02	2.27	2.52	2.86	3.14	**4.09**	9-11 pm
3-hour	2.12	2.38	2.66	3.04	3.35	**6.10**	9-midnight
6-hour	2.48	2.8	3.14	3.61	3.99	**6.85**	9pm-3am

Areal reduction for the various storm frequencies (table 2) were of the “fixed” type, whereby the reduced rainfall value is applied to the entire storm area. These are not considered applicable to observed storms. In the absence of observed storm ARFs for the area, the reductions applied to the observed precipitation of September 2013 were taken from fixed ARF of figure 7; however the precipitation value applied to any given sub-basin was a reduction of the centered maximum value, proportional to the distance of the sub-basin from the storm center (assumed to be near the confluence of the upper Whitewater and SF Whitewater Creek, upstream of the Catwalk gage, figure 3).

The resulting model hydrograph at the USGS Catwalk gage, compared to the observed, is shown in figure 10. The two graphs are so remarkably close that the following points should be noted.

The model parameters were not adjusted in order to make the output match the observed. The same watershed scenario for postfire, after one year, was used here as for the modeling of recurrence flows. However, the model hydrographs of figure 10 is the result of only one possible scenario of storm size and centering. Other centerings could be justified using the same observed data. The assumed reduction of hydrophobic effect for the one year post-fire condition seems to have been in the ballpark, but the widespread nature of unknowns makes for difficulty judging which assumptions were better than others.

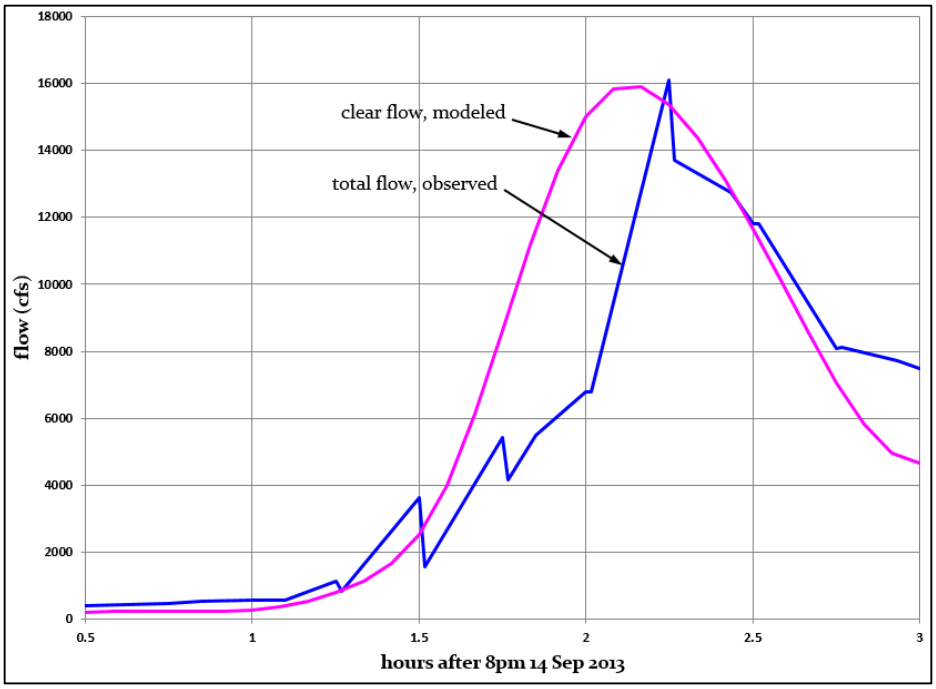

Figure 10 Catwalk gage modeled versus observed for the storm of 14-15 September 2013.

CONCLUSIONS

This case study has shown that reasonable model results can be obtained using the modeling options of HEC-HMS, Green-Ampt infiltration, and GIS-derived synthetic unit hydrographs. The extent of hydrophobicity and its effect on runoff remains a major source of uncertainty, but the assumptions made for Whitewater Creek, informed by detailed mapping of burn severity, appear to have resulted in a useful model.

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