ESTIMATING POST-FIRE PEAK FLOWS FOLLOWING THE SCHULTZ FIRE, COCONINO NATIONAL FOREST, ARIZONA

Karen A. Koestner,[1] Peter E. Koestner,[2] Daniel G. Neary

Wildfire is a major land management concern due to direct impacts of fire on forest resources, and potentially negative effects on landscape processes by altering watershed function. This often results in increasing rates of runoff, erosion, downstream sedimentation, and overall site degradation (DeBano et al. 1998, Neary et al. 2005, Robichaud et al. 2010). In the United States the number of fires has been increasing over the last decade, as have fire size and severity (National Interagency Fire Center 2009). The latent disturbance of post-fire flooding can be sustained for multiple years as watersheds recover. Though post-fire flooding is modeled and estimated, it is largely unpredictable in the Southwestern USA due to the variability of high-intensity monsoon precipitation, basin characteristics, and burn patterns.

Consumption of tree canopies and herbaceous vegetation results in a nearly complete reduction of interception from severely burned watersheds. Infiltration is also impacted due to the removal of the litter and duff organic layer. Without the spongy organic surface, the residence time of water on the forest floor (now scorched mineral soil) is drastically reduced causing excessive runoff generation. Soil water repellency also prevents infiltration into the soil profile, and produces increases in runoff from burned watersheds. Increases in the amount of precipitation that becomes runoff can result in peak-flows over an order of magnitude greater than those observed prior to wildfire (Neary et al. 2005).

Increases in post-fire peak flows result in a change in the shape of the storm-runoff hydrograph for a given precipitation event. Post-fire flow events tend to be significantly higher in magnitude than pre-fire flow events while maintaining a similar duration of pre-fire stormwater runoff (Earles et al. 2004, Nelson et al. 1999). Following the 1996 Chino Well Fire in SE New Mexico fire, the Mud Canyon Basin produced a 100-year runoff event in response to a 5-year storm (Nelson et al. 1999). The 2000 Cerro Grande Fire in north central New Mexico resulted in similarly drastic increases in post-fire peak-flows. Earles et al. (2004) modeled pre-and post-fire flows for the Cerro Grande Fire using HEC-1 to simulate pre-fire and post-fire storm flow for the Pueblo Canyon watershed and showed a 663% increase in peak flow and 336% increase in total runoff from the watershed after the fire, without an increase in the duration of stormwater runoff. Post-fire peak-flow magnification tends to lessen as the number of years since the fire increases and watersheds are able to recover and revegetate.

These changes in hydrologic response cause flood hydrographs to be flashier, creating an extremely hazardous situation. Predictions of post-fire flood flows are challenging due to the fact that watersheds are severely altered. Also, the response from one precipitation event is not going to necessarily mimic another depending on the antecedent soil moisture conditions and the erosive and depositional processes that have occurred from previous events. In the Southwest, summer monsoons complicate prediction further because these rainfall events are short-duration, high-intensity, and can be limited to a small area of impact.

The Schultz Fire

From June 20th to July 30th 2010, the Schultz Fire burned 6,100 ha on the eastern slopes of the San Francisco Peaks, (Figure 1). This was a wind driven fire, consuming approximately 60% of the total burn area in the first day. Ponderosa pine and mixed conifer forest on steep to moderate slopes of the mountain front and upper piedmont zone of 11 ephemeral watersheds were impacted (Youberg et al. 2011a). Seventy percent of the Schultz Fire was classified as high to moderate severity, while 25% was classified as low severity, and another 8% was unburned (USDA Forest Service 2010). The high-severity burned areas are concentrated on the steep mountain face with slopes greater than 30% and in places exceeding 100%.

Prior to the fire and subsequent flooding, the upper mountain had few defined channels consisting largely of ridge-swale topography with thick mixed-conifer forest cover and a well-developed O horizon (10-30 cm). These swales become more defined channels in the lower elevation ponderosa pine-dominated piedmont zone. According to residents living downstream of the burn area, these channels rarely carried flows prior to the Schultz Fire. The slope varies from 60% to >100% on the upper mountain face to 30% to 60% in the piedmont zone and to 5% to 7% at the head of the alluvial fans (Koestner et al. 2011). Scattered housing developments, most of which are less than 40 years old, occupy the fans.

The onset of the monsoon season in mid-July 2010, the 4th wettest on record, resulted in debris deposition on the alluvial fan from a series of discrete flood events over the following 6-weeks of summer precipitation. Over 1000 residents in this area were evacuated from their

1 US Forest Service, Rocky Mountain Research Station, Flagstaff, AZ
2 US Forest Service, Rocky Mountain Research Station, Phoenix, AZ

homes during the fire itself and many experienced damages to property due to repeated post-fire flooding.

Post-fire debris flows scoured the swales on the upper slopes of most watersheds 1-4 m deep thereby exposing bedrock (Neary et al. 2011, Youberg et al. 2011b). Well-defined channels in the piedmont zone were filled with coarse material from debris flows and flood-flow bedloads in less confined reaches. In confined reaches, channels incised over a meter beneath the previous channel surface from a season of monsoon precipitation. The piedmont channels coalesced and diverged onto an alluvial fan surface that was constantly being reworked by multiple flood events. As defined channels emerged onto fan heads, flood flows dispersed out into sheet flows across the alluvial fans and outwash-plain, passing through Coconino National Forest lands and several residential developments (Figure 1) (Koestner et al. 2011).

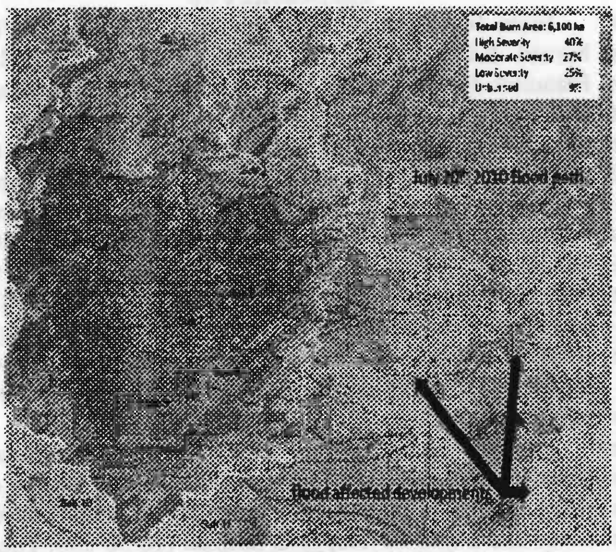

Figure 1. Outline of Schultz Fire with shaded severity and an estimated outline of the July 20th flow path and impacted developed area.

Burned Area Emergency Response

Burned Area Emergency Response (BAER) teams are sent in after moderate to large fires to determine immediate risks to resources post-fire and prescribe actions to reduce these risks. Principal BAER mitigation goals are to reduce flooding potential and retain on-site soils (Robichaud and others, 2010). Prior to containment of the Schultz Fire, a U.S. Forest Service (BAER) team began to assess the fire impacts, identify potential resources at risk, and determine appropriate mitigation measures. Of particular concern was the City of Flagstaff's waterline road (FR146), which provides approximately 20% of Flagstaff's summer water from the Inner Basin of the San Francisco Peaks. Other resources and risks that were evaluated included cultural resources, soil erosion, and flooding impacts to downstream developments (U.S. Forest Service 2010).

METHODS

Manning Based Peak-Flow Estimation

Peak-flow estimates following the July 20th flow event were completed using the Manning Equation. This is an indirect peak-flow estimation method that relies on watershed characteristics and post-flow field observations of high-water, cross-sectional area, and wetted perimeter. A high roughness coefficient of 0.05 was used to estimate flows from the July 20th because prior to that event the only previous flow in the channels was minimal and there was no scour or other smoothing factors.

Manning Equation: $Q = (1/n)(AR^{2/3})(S^{1/2})$

where: Q = discharge (m^3/sec or cms)
n = Manning's roughness coe fficient
A = cross-sectional area (m^2)
WP = wetted perimeter or length of channel bottom and bank sides between cross-section endpoints (m).
R = hydraulic radius (A/WP) (m)
S = channel slope

Beginning at the southern end of the burn area (Figure 1), channels cross-sections were systematically surveyed at each distinct channel formation encountered along a longitudinal transect in the piedmont zone (Figure 2). This transect was placed 20 to 30 m upstream of a powerline road that runs north-south parallel to the mountain front. This feature was chosen as a basis for establishing channel surveys because it crosses the extent of the burn area down-slope of the San Francisco Peaks. Channel width and depth were surveyed between two permanent upslope rebars. Channel depth was then measured at the thalweg 50 m upstream and 50 m downstream of the cross-section to estimate channel slope.

BAER Hydrologic Modeling

The US Forest Service BAER team used a runoff curve number model, "WILDCAT4" to grossly estimate pre- and post- fire runoff from the 11 watersheds affected by the Schultz Fire prior to the onset of monsoons (Higginson 2010). This model relies on Natural Resource Conservation Service (NRCS) curve numbers and designed rainfall events to predict hydrographs. Initially a 25-yr event was used to estimate peak-flows but that produced flood flows outside a treatable range. Since erosion prevention and landscape treatments are the goal of the BAER team, a 10-yr rainfall event was used instead. A 10-year storm for this region is equivalent to 4.06 cm (1.6 in) over 1-hour interval (NOAA 2004; http://hdsc.nws.noaa.gov/hdsc/pfds/sa/az_pfds.html). The design storm took into account regional summer precipitation patterns by concentrating 50% of the total precipitation in the first 10 minutes of a 1 hour storm.

RESULTS AND DISCUSSION

Thunderstorms on July 20, 2010 over the Shultz Burn area delivered 4.52 cm (1.78 in) of rainfall in 45 minutes, with a 10 minute peak-intensity of 2.4 cm (0.98 in). BAER modeling used a design storm for post-fire peak flow estimation with a 1-hour cumulative rainfall of 4.06 cm (1.6 in) and a 10-minute peak intensity of 1.96 cm (0.77 in). Actual precipitation on July 20th that resulted in substantial flooding had 11% more total rainfall, and 19% higher 10-minute peak intensity than the 10-year return interval design storm.

The channels surveyed for peak-flow estimates of the July 20th event did not take into account the watershed delineation completed by the Coconino National Forest. These surveys were based solely on channel features encountered on the ground and were quite different from the watershed outlets used for the BAER hydrologic modeling (Figure 2). The variability between watershed outlets and channel formation on the ground is due to the limits of using coarse-scale GIS data (10 m digital elevation model) to determine watershed boundaries. Elevation differences between channels across the alluvial fan are minimal which leads to potential errors in estimating watershed outlets. However, this should not have a substantial impact on the peak-flow modeling due to the fact that variables such as channel slope, total relief, and watershed area are not affected.

The results included here are for only 7 of the watersheds within the burn area. Peak-flow estimates calculated using the Manning equation are shown in Table 1. Peak-flow estimates from multiple channels are combined for the purpose of comparison to BAER modeling efforts as shown in Table 2. This is due to the fact that there are multiple flow paths from a given watershed not accounted for by a single outlet. Also, these estimates do not take into account the contribution of overland sheet flows that occurred during the July 20th event.

The indirect measurements of peak-flows from the July 20th event are on average, approximately 7 times greater than the modeling efforts undertaken by the BAER team prior to the onset of monsoons. Although there is some variation between the design storm and the actual precipitation event on the 20th of July, 2010, (10-20%) this is a fairly close comparison. The BAER team Hydrologist Specialty Report also included pre-fire peak-flow estimates for the same design storm. The BAER post-fire predictions were on average 8.5 times greater than modeled pre-fire peak-flows, while RMRS estimated peak-flows from July 20th were ~55 times greater than pre-fire modeling.

The discrepancy between post-fire modeling and peak-flow estimates from July 20th could be amplified by over-estimation using the Manning equation for this assessment (Jarrett 1987). Over-estimation is common in high-gradient channels (slopes >0.2%) due to the turbulence of flows in these channels, and the fact that they do not often have uniform flow. It is likely that the estimates determined from the July 20th event are too high, and those modeled by the BAER team are too low. Neither of these estimates take into account the bulk of sediment in the flow, and are limited to variables that can be subjective to determine and difficult to apply widely (Curve Number for the WILDCAT4 modeling, and roughness coefficient for the Manning equation). Regardless, the comparison of indirect estimates of flow event magnitudes (Manning) to BAER predictions (WILDCAT4) provides a forum of discussion on how to improve post-fire flooding prediction and preparedness.

CONCLUSIONS

In a post-fire environment, with large portions of steep watersheds burnt at high-severity, the landscape is subject to rapid change with each precipitation event compared to pre-fire conditions. These changes result in considerable increases in runoff and peak-flows, as well as substantial erosion and sedimentation. Pre-fire instrumentation of burned watersheds rarely occurs, so modeling is used to predict post-fire watershed responses. In most instances, model simulations underestimate peak-flows that can range from 5 to 2,500 times the pre-fire peak-flows (Neary et al. 2005). Post-flow field observations of high-water, surveys of cross-sectional areas, and determination of wetted perimeter provide field-based estimates of post-fire peak-flows, but these values may be over-estimates for high-gradient turbulent flows. Crest-stage gages can improve these estimates providing that they can be installed quickly after a wildfire is contained. In the case of the Schultz Fire of 2010, BAER Team modeling using the WILDCAT 4 hydrologic model predicted a peak-flow increase 8.5 times pre-fire conditions. While this figure was within the range observed for fires in the Southwest USA, it was considerably lower than the 55-fold flow increase estimated by actual channel surveys. Better estimates of post-wildfire peak-flows are needed for providing accurate advice to county and state emergency managers on the potential magnitudes of post-fire floods. Modeling and measurement of post-wildfire peak-flows should continue to provide data for making better refinements of post-fire peak flood flow responses.

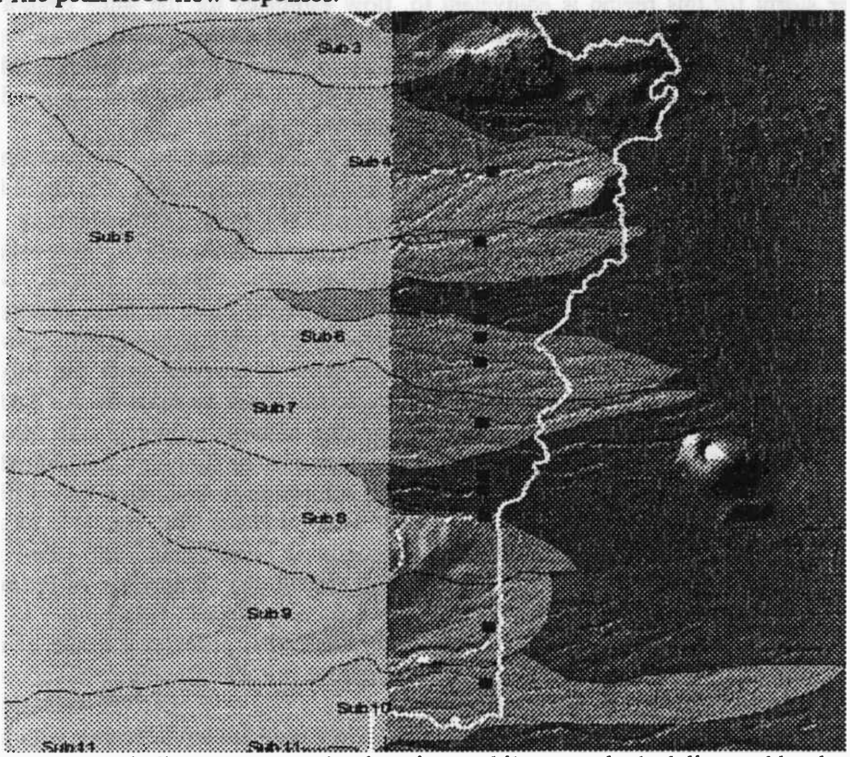

Figure 2. Black squares indicate cross-section locations, while watersheds delineated by the BAER team are shaded in light grey. Cross-sections locations were identified by evidence of channel flow while walking a transect south to north across the burn area.

Table 1. Variables used to calculate peak-flows with the Manning equation for select watersheds (see formula above). WS ID is the corresponding watershed that the BAER team designated; XS is the cross-section number as encountered in the field (south to north). The row shaded in grey is not used in comparison to BAER estimates, while the remaining rows are grouped by watershed for comparison in Table 2.

WS ID	XS	A (m^2)	WP (m)	R (m)	S	V (m/s)	Q (cms)
4M	CF13	11.6	14.14	0.82	4.8%	3.84	**44.54**
5M	CF12	21.8	25.35	0.86	5.3%	4.18	**91.11**
5S	CF11	0.8	4.37	0.18	4.8%	1.41	**1.13**
5/6?	CF09	4.7	25.24	0.19	5.4%	1.51	**7.10**
5/6?	CF10	12.5	24.24	0.52	5.1%	2.90	**36.24**
6M	CF07	8.9	34.60	0.26	6.2%	2.02	**17.96**
6N1	CF08	1.3	5.80	0.22	6.8%	1.93	**2.51**
7M	CF06	2.2	5.51	0.40	5.4%	2.51	**5.52**
7N	CF05	11.7	37.92	0.31	5.2%	2.09	**24.46**
7S	CF04	4.80	72.44	0.07	4.4%	0.69	**3.29**
8M	CF03	9.2	12.89	0.71	4.4%	3.35	**30.83**
9M	CF02	8.4	53.20	0.16	3.3%	1.06	**8.90**
10M	CF01	12.1	17.58	0.69	3.1%	2.75	**33.22**

Table 2. Comparison of BAER 10-year storm peak-flow predictions pre and post fire to the indirect peak-flow estimates from the July 20th, 2010 event using the Manning equation. Note, stared* watersheds include values from grouped channels to roughly estimate the peak-flow from the entire watershed as outlined in Table 1. BAER data from Higginson 2010.

WS ID	BAER Wildcat4 Pre-Fire Peakflow (cms)*	Post-Fire Peakflow (CMS)		Comparisons (x - difference)		
		BAER -Wildcat4	RMRS -Manning	BAER post/ BAER pre	RMRS post/ BAER post	RMRS post/ BAER pre
		10-yr event (cms)	7/20/10 event (cms)			
4	0.71	6.91	44.54	10	6	63
5*	1.5	14.69	92.24	10	6	61
6*	0.28	2.27	20.47	8	9	73
7*	0.57	6.14	33.27	11	5	58
8	0.31	1.95	30.83	6	16	99
9	0.82	9.31	8.9	11	1	11
10	1.61	5.63	33.22	3	6	21
averages:	*0.83*	*6.70*	*37.64*	*8.51*	*7.12*	*55.23*

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