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Curve Number and Peakflow Responses Following the Cerro Grande Fire on a Small Watershed

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Abstract

The Curve Number (CN) method is routinely used to estimate runoff and peakflows following forest fires, but there has been essentially no literature on the estimated value and temporal variation of CNs following wildland fires. In May 2000, the Cerro Grande Fire burned the headwaters of the major watersheds that cross Los Alamos National Laboratory, and a stream gauging network presented an opportunity to assess CNs following the fire. Analysis of rainfall-runoff events indicated that the pre-fire watershed response was complacent or limited watershed area contributed to runoff. The post-fire response indicated that the complacent behavior continued so the watershed response was not dramatically changed. Peakflows did increase by 2 orders of magnitude following the fire, and this was hypothesized to be a function of increase in runoff volume and changes in watershed network allowing more efficient delivery of runoff. More observations and analyses following fires are needed to support definition of CNs for post-fire response and mitigation efforts.

Introduction

The importance of understanding the impacts of wildland fire on hydrologic response is escalating because of the greater demand that humans have placed on wildlands and the proximity of human development to many areas and forest in particular. Moody and Martin (2001) have provided a thorough review of the hydrologic effects of forest fire, and the essential results are that increases in runoff volume and peakflows are usually observed. Accordingly there is a critical need to develop fire-affected rainfall-runoff parameters for use in design, planning, and post-fire evaluations. A critical development that is needed is the estimation of rainfall-runoff parameters for prediction of the effects of fire effects. Beven (2000) indicates that one of the reasons for hydrologic modeling is to predict the effects of land use change, and fire represents one of the most drastic types of land use change.

The Cerro Grande Fire occurred in May – June 2000 and burned 42,878 acres (173.5 km^2) on the Pajarito Plateau in northern New Mexico including watersheds whose streams flow through Los Alamos National Laboratory (LANL). The headwaters were categorized as high burn severity, which means that the duff layer was removed, the soil surface was heated, and the vegetative canopy was burned. The reduced vegetation affects runoff by decreased interception meaning that more water will arrive at the soil surface, and less vegetation reduces the evapotranspiration, which translates to higher soil water content than before the fire. Surface heating of the soils can create hydrophobic conditions, which lower the soil's infiltration capacity.

Fortunately, a pre-existing stream gauging network at LANL provided an opportunity to examine post-fire hydrology. There are different hydrologic techniques to evaluate the effects of fire on soil hydrology. Moody and Martin (2001) reported on a number of paired watershed studies that were available in the literature. Martin and Moody (2001), Pierson et al. (2001), and Johansen et al. (2001) all employed different rainfall simulation methods to measure infiltration rates with a logical extension that these rates can be used to parameterize an infiltration based hydrologic model such as that described by Beeson et al. (2001). For our analysis of the Cerro Grande Fire, we selected the Curve Number method (CN), which has a long history of use Soil Conservation Service (1958) and is applied to fire impact analysis.

Methods

Watersheds. The analyses focus on watersheds that are headwaters to canyons that run west to east from the Jemez Mountains to the Rio Grande. These are as Pajarito, Water, and Starmer Canyons, and their locations are given in Figure 1. All three canyons were affected by the Cerro Grande Fire. The gauging stations drainage area are 1216 ac. (4.9 km^2) for Pajarito, 2170 ac. (8.8 km^2) for Water and 525 ac. (2.12 km^2) for Starmer. Approximately 55 percent of the area in the Starmer watershed was classified as high burn severity. Following the fire, a number of remedial actions were employed to reduce the threat of flooding and erosion. The actions taken following the Cerro Grande Fire were rapid and extensive because of LANL facilities that were at risk. In the results that follow, this can be considered a "best case" for mitigating the impacts of forest fire on hydrologic response.

Data. The LANL Environmental Stewardship Division Water Quality and Hydrology Group (ENV-WQH) maintains a surface water gauging network that is described in a series of annual reports by Shaull et al. (1996, 1996, 1998, 1999, 2000, 2001, 2003, and 2002). Following the Cerro Grande Fire and in particular the event of June 28, 2000, many of the headwater gauging sites were destroyed. The only headwater gauge that functioned from June 2000 to September 2003 was E242, which is Starmer Canyon (Figure 1) so the data from that station are the primary data for analysis of the post-fire response in this paper. One issue with the Starmer is that it began operations in 1999 a year before the Cerro Grande Fire so pre-fire relationships cannot be developed. Therefore, data from E240 (Pajarito Canyon at NM 501) and E252 (Water Canyon at NM 501) will be used to represent pre-fire conditions for the headwater areas.

Rainfall data for the analyses were available from three sources. The ENV Meteorology and Air Quality Group (ENV-MAQ) maintain a weather observation network for Los Alamos National Laboratory. The primary weather station is located at Technical Area (TA) 6 (Figure 1), which is east of Starmer Canyon, and the other ENV-MAQ is located on Pajarito Mountain (Figure 1), which is northwest of Starmer Canyon at an elevation of 10,360 ft (3156 m). Both ENV-MAQ sites use a tipping bucket rain gauge and rainfall amounts are reported every 15 minutes. Data from these gauges were available both before and after the Cerro Grande Fire. The other source of rainfall data was from the post Cerro Grande period when a Remote Automated Weather Station (RAWS) was installed in Pajarito Canyon (Figure 1). The Pajarito RAWS is located approximately midway in terms of distance between the TA-6 and Pajarito Mountain gauges, and the elevation of the Pajarito RAWS gauge is 8350 ft. (2545 m). The Pajarito RAWS gauge is closer to TA-6 in terms of elevation than Pajarito Mountain. The data for the RAWS gauge is available at the following web site http://www.losalamos.dri.edu/index.html and the data are reported in one-hour increments. The one-hour increments available for the RAWS gauges are not adequate for determining the rainfall hyetograph so the RAWS total was weighted by the TA-6 gauge 15-min. distribution to obtain the hyetograph. Another key point is that the Cerro Grande Fire occurred during a major drought in the southwestern U. S., which affected the number of rainfall events that occurred after the fire.

The rainfall amount and distribution for a runoff event are determined by examining the hydrograph and finding the corresponding rainfall sequence. This can be simple in the case of a single event on a day, or more complicated if a low intensity, long-duration event occurs such as the series of storms in October, 2000.

Runoff data from the June – September period for the years 2000 – 2003 that coincides with the summer monsoon were obtained from the gauging station records that are maintained on the ENV-WQH HYDRON® database. The runoff data were available in 5-minute increments. Each hydrograph was extracted beginning with the time when rainfall started based on the ENV-MAQ gauges and ended when the hydrograph returned to a low steady value. The peakflow for the runoff period was the maximum observed 5-min. value. Total runoff for an event was determined by integrating the hydrograph. The pre-fire event totals were 25 for Pajarito Canyon (E240) for the period 1995 – 1999 and total of 23 events for Water Canyon (E252) for the period from 1996 to 1999. For Starmer Canyon, 14 events were available from June 2000 to September 2003.

CN analysis. Rainfall-runoff data to assess recovery was analyzed using the USDA Soil Conservation Service Curve Number (CN) method. The CN technique was developed to predict direct runoff from rainfall events considering soils, land cover, and management practices. Documentation for the CN method can be found at http://www.wcc.nrcs.usda.gov/water/quality/hydro/Information___References/National_Engineering_Handbook/national_engineering_handbook.html . The CN approach was used by the Burned Area Emergency Rehabilitation (BAER) Team to estimate runoff and peakflows following the Cerro Grande Fire. The CN option in the U. S. Army Corp of Engineers Hydrologic Engineering Center (HEC) 1 computer code was used by

McLin et al. (2001) to estimate runoff and flood flows for Los Alamos National Laboratory sites.

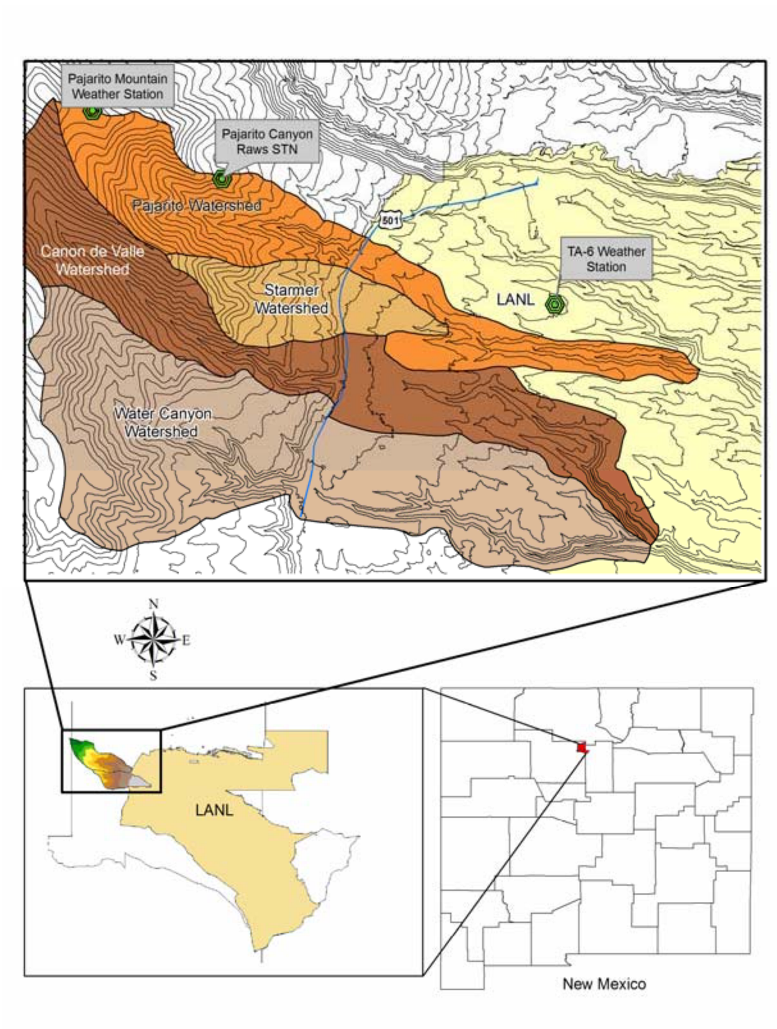

Figure 1. Location of watershed used in the analyses along with precipitation gauges.

The CN method calculates runoff volume from a total rainfall using the following equation

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (1)$$

where: Q = direct storm runoff (in.), P = total storm rainfall (in.), and S = retention parameter (in.). Equation 1 is for P≥0.2S, Q=0 otherwise. The CN is used to define S by the following relationship

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

where: CN = curve number ($0 \leq CN \leq 100$). When used in planning or design the CN values are selected from handbook tables based on soils and land condition. When event rainfall and runoff data are available, the CN can be calculated from observed data. The latter approach requires solving Equation 1 for S Hawkins (1973), which gives

$$S = 5\left(P + 2Q - \sqrt{4Q^2 + 5PQ}\right) \qquad (3)$$

where all variables have been defined. The CN in English units (i.e., S in inches) is calculated from inverting Equation 2.

This paper derives CNs from rainfall-runoff data using Equations 3 and 2 comparing post-fire response from the period 2000 – 2003, and to pre-fire data from Water and Pajarito Canyons.

Results and Discussion

Forested watersheds. Many small watersheds with distinct forest cover and deep soils in moist settings display what has been termed a complacent behavior (Hawkins 1992; Hawkins 1993). That is, with little or no overland flow runoff for most storms, but deriving storm flow from direct channel interception and near-channel impervious areas. This is consistent with the classical forest hydrology concepts advanced by Hewlett and Hibbert (1967). However, this genre of rainfall runoff responses contrasts clearly with response patterns from most agricultural and urban watersheds, and many rangeland watersheds, which usually follow a traditional curvilinear response path, and are driven by infiltration-limiting processes.

Because the channel source areas are a small part of the watershed area, the watershed unit runoff is correspondingly small, and the runoff fraction (Q/P) is easily interpreted as the impervious (flowing channel and near channel) area fraction. Accordingly, the rainfall-runoff relation is can be expressed as Q=CP, with C being the source area fraction.

The complacent response shows up clearly in small watershed rainfall-runoff data. Table 1 shows this behavior for a number of undisturbed small forested watersheds, all of which support baseflow. Note that "C" is quite modest - on the order of 1/10 to 2 percent, and that the linear r^2 is high. These low runoff watersheds are not uncommon in western forests.

Curve numbers. Under such special source area conditions, the CN is a function of C and P. Beginning with the solution for S in Equation 3 and inserting Q=CP leads to

$$S = 5P[1+2C-\sqrt{(4C^2+5C)}] = 5Pf(C) \qquad (4)$$

where f(C) is the expression inside the brackets []. Thus Equation 2 becomes

$$CN = 1000/(10+S) = 100/(1+Pf(C)/2) \qquad (5)$$

The P-CN plots for the watersheds listed in Table 1 are shown in Figure 2 along with the post-fire values from Starmer Canyon provided in Table 2. The solid line in Figure 2 represents CN_0 which is the rainfall depth where P=0.2S and is derived from Equation 2

$$CNo = \frac{100}{\left(1+\frac{P}{2}\right)} \qquad (6)$$

where all variables have been defined. CNo represents a lower rainfall limit and from Figure 2, it can be seen that the complacent watersheds in Table 1 and Starmer Canyon follow the CNo line trend over the range of rainfall values presented.

Table 1. Rainfall runoff characteristics of selected forested complacent watersheds in the western U.S.

		Dates					
Name	**State**	**From**	**To**	**C**	**r^2**	**Se(in)**	**Reference**
N Thomas	AZ	1965	1970	0.0008	79	0.0006	Anderson (1975)
S Thomas	AZ	1963	1970	0.0010	48	0.0011	Anderson (1975)
Mo Gulch	CO	1940	1959	0.0030	79	0.0011	Hawkins (1961)
Eggers	ID	1969	1978	0.0048	87	0.0015	McGurk (1982)
Control	ID	1969	1976	0.0054	53	0.0030	McGurk (1982)
Cabin	ID	1970	1978	0.0046	43	0.0032	McGurk (1982)
Ditch	ID	1969	1975	0.0043	76	0.0024	McGurk (1982)
C Creek	ID	1970	1978	0.0206	64	0.0126	McGurk (1982)
D Creek	ID	1969	1978	0.0159	64	0.0105	McGurk (1982)
Murphy	ID	1967	1977	0.0074	24	0.0105	McGurk (1982)
W Chicken	UT	1962	1971	0.0096	67	0.0070	Johnston & Doty (1972)
E Chicken	UT	1962	1971	0.0048	91	0.0013	Johnston & Doty (1972)
Halfway	UT	1940	1966	0.0113	90	0.0038	Walker (1970)

Notes: C is the least squares fit to Q=CP; r^2 in percent. All data from U.S. Forest Service sources. Chicken Creek dates are approximate

Fire Effects. Watershed disturbances such as roads, grazing, logging, or fires can alter the source area arrangement of a complacent watershed, causing higher runoffs and displaying higher CNs. Subsequent regrowth and recovery eventually return the watershed hydrology to its prior status. The assumption is that the watershed behavior has been altered away from the complacent response by the loss of vegetation and hydrophobic conditions moving the watershed towards the standard response noted by Hawkins (1993). This assumption is generated by the marked increase in peakflows observed following fires as the runoff volume response.

Figure 3 shows CN-P plots for the pre-fire LANL watersheds, Water Canyon and Pajarito Canyon. The post-fire Starmer Canyon events are superimposed. The Starmer CNs are elevated by the fire response, but Starmer Canyon still bears much of the complacent characteristics that preceded the fire exhibiting an extreme of complacent behavior. Runoff is still a minor part of the rainstorm, but nevertheless several times the complacent pre-fire expectations. It is not, however, the elevated CN response or behavior usually found in an ordinary (and even well-managed) agricultural or urban watershed.

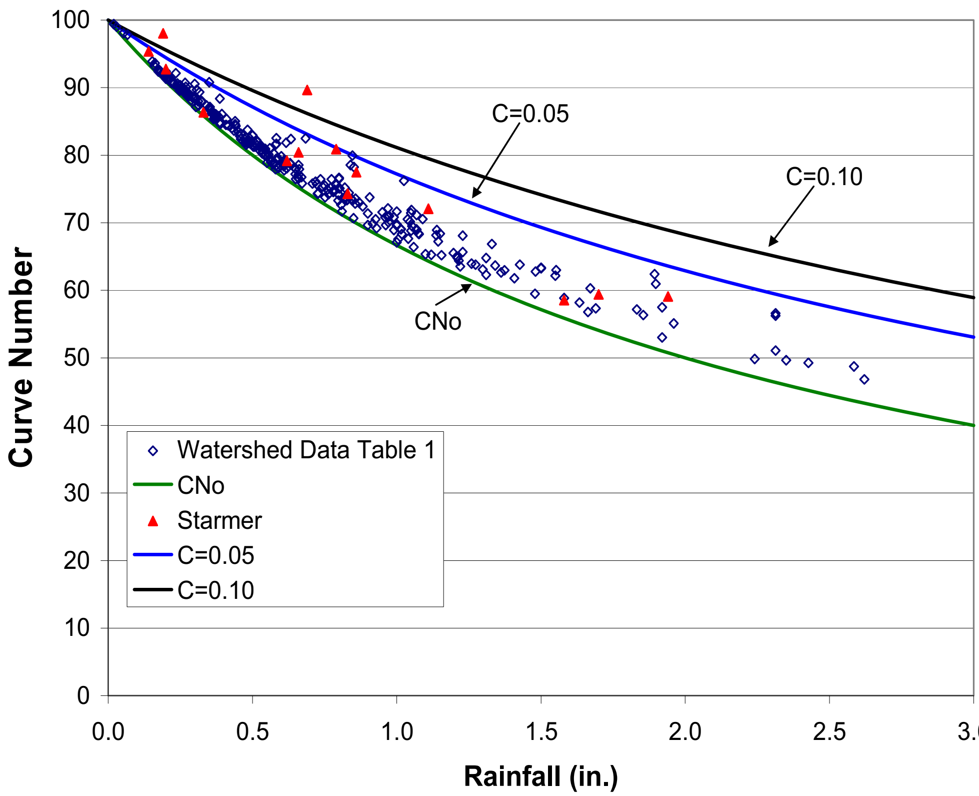

Figure 2. Curve Number as a function of event rainfall for the 13 small forested watersheds given in Table 1 displaying complacent behavior. The data are composited. Post-fire Starmer Canyon is shown as triangles.

We suggest that this comparative hydrology gives insights to the scale of fire responses. The low extremes of pre-fire response are generally unappreciated with the CNo curve providing an estimate for the lower limits of Starmer Canyon pre-fire CN values. Fire response - as seen with the Starmer data - is still modest in an absolute and comparative terms, but several times the pre-fire responses. This is a significant increase in CN, but it is not obvious that Starmer Canyon has changes its behavior from a complacent watershed is especially true when compared to the larger range of complacent watersheds in Figure 2. Stable channels and flow paths formed during the long pre-fire intervals are susceptible to even the limited higher flows.

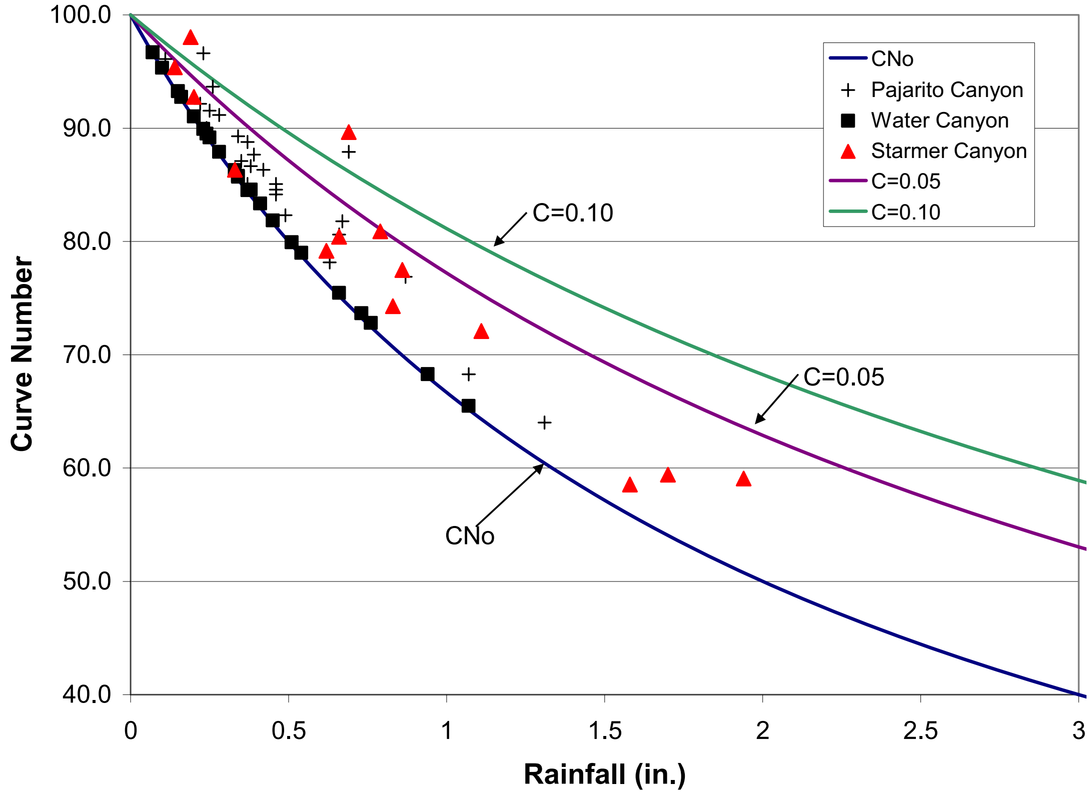

Figure 3. Curve Number-rainfall plot for three Los Alamos watersheds. The points for Water Canyon and for Pajarito Canyon are pre-fire conditions. They display complacent response. As identified, the "▲" symbols represent Starmer Canyon following the fire. Note the general concordance with the Pajarito and Water Canyons unburned events.

Peakflow analysis. Changes in the magnitude of the CN are not nearly as dramatic as the changes in peakflow rates following fires. The limited operation of the Starmer gauge prior to the fire again restricts any inference as to relative post-fire peakflow behavior. The Pajarito Canyon gauge at State Highway 501 (E240), which operated for a longer period of time prior to the fire, had a maximum observed pre-fire peakflow of 0.002 in/hr, but the Pajarito Canyon gauge site has a larger area and steeper slopes than Starmer. The peakflow rates in Table 2 are two orders of magnitude larger than the pre-fire value from Pajarito Canyon. This response is expected given literature on post-fire hydrologic behavior (Moody and Martin, 2001).

The sensitivity of peakflow in describing the hydrologic response following a fire has been recognized (Moody and Martin, 2001). The three events in October 2000 were long duration and low intensity, and the effects can be seen on the peakflow rate. The peakflows for these October events are greater than the pre-fire, but do not approach that of June 28, 2000 even though I_{30max} for the October 27 event is as large as the June 28, 2000 event.. The sequence of events on August 28 and 29, 2003 did not generate a large peakflow although the lower rainfall amount on August

29 did generate flow that may not have been produced under pre-fire conditions. The trend in Starmer peakflows in Table 2 is declining over time. By 2003, the peakflow values appear to be of the same order of magnitude as the pre-fire values. The post-fire trends in CN and peakflows in Table 2 are not readily explained and will be a topic of future research.

Table 2. Storm events from Starmer canyon following Cerro Grande Fire for the period June 2000 to September 2003.

Date	Pajarito RAWS rainfall (in.)	Runoff (in.)	S (in.)	CN	Peakflow (in/hr)	I_{30}max (in/hr)
6/28/2000	0.69	0.1308	1.15	89.7	0.317	1.05
7/8/2000	0.66	0.0114	2.44	80.4	0.042	0.67
10/7/2000	1.11	0.0382	3.60	73.5	0.003	0.18
10/22/2000	1.95	0.0506	6.71	59.9	0.011	0.36
10/27/2000	0.91	0.0304	2.97	77.1	0.013	1.07
8/5/2001	0.20	0.0643	0.22	97.8	0.264	0.66
8/9/2001	0.80	0.0421	2.33	81.1	0.052	0.88
6/21/2002	1.28	0.0155	4.97	66.8	0.023	1.52
7/4/2002	0.33	0.0001	1.58	86.3	0.001	0.56
7/14/2002	0.20	0.0023	0.78	92.8	0.004	0.96
8/11/2003	1.58	0.0037	7.08	58.6	0.004	0.54
8/28/2003	0.62	0.0032	2.63	79.2	0.002	0.14
8/29/2003	0.14	0.0034	0.49	95.4	0.002	0.20
9/6/2003	0.83	0.0053	3.46	74.3	0.002	0.26

We have included the maximum 30-minute intensity (I_{30}max) as an indicator of rainfall intensity following the example of Moody and Martin (2001). A plot of the peakflow versus I_{30}max is given in Figure 4. The 30-minute intensities for 2-, 10-, and 100-year return periods were obtained from the web version of NOAA Atlas 14 (Bonnin et al. 2004) using the coordinates of the Pajarito RAWS site. During the post-fire period, all but one of the event rainfall intensities were less than the 2-year rainfall intensity so the changes in peakflow are caused by changes in surface properties rather than high rainfall intensities. The ratio of the peakflow to I_{30}max is low, which is consistent with the complacent nature of this watershed found in the CN analysis. Still, these are peakflows of record when compared to the pre-fire values from adjacent watersheds despite the complacency and rehabilitation efforts.

Conclusions

The hydrologic effects of wildland fires have been documented, but there has been little effort at developing and testing tools to predict post-fire conditions and/or recovery of hydrologic conditions to a new post-fire equilibrium. The CN method has been used to predict the hydrologic effects of fire, but there is essentially no analysis of CN magnitude or behavior following fires. The stream gauging network at LANL provided an opportunity to study post-fire hydrologic response and to quantify CNs for future use.

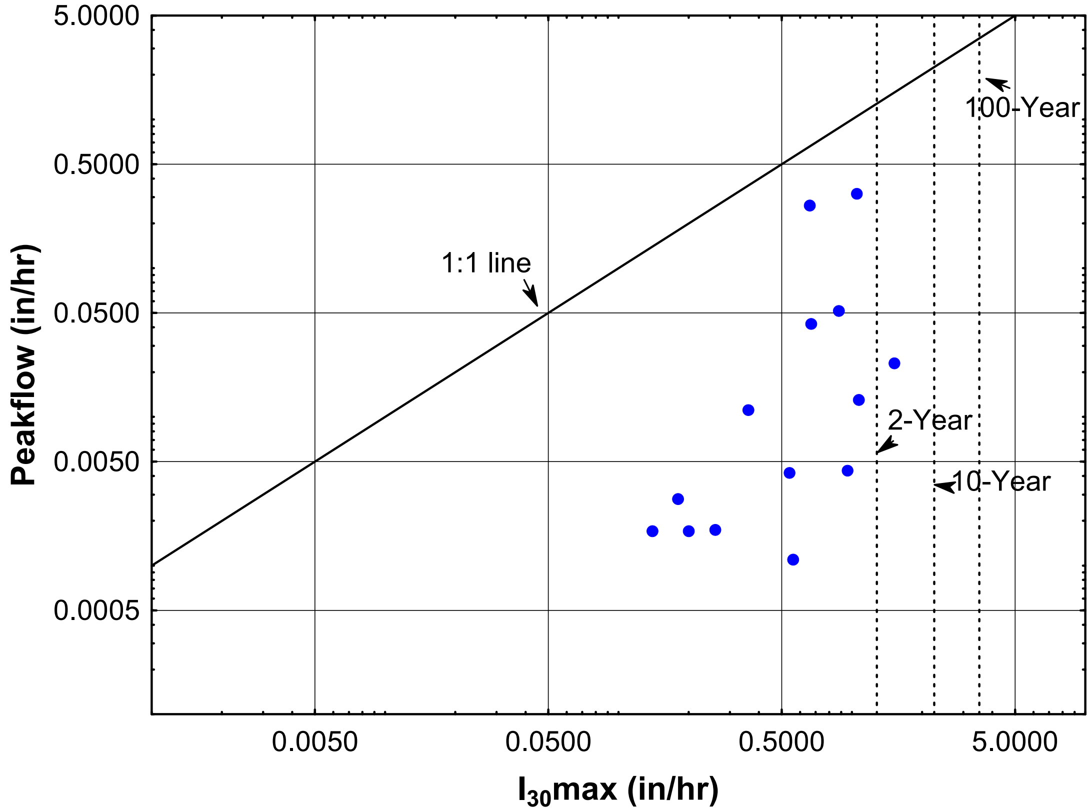

Figure 4. Peakflow versus maximum 30 minute intensity (I_{30}max) for post-fire events from Starmer Canyon. The dash lines are the NOAA Atlas 14 estimated 30 minute intensities for the 2-, 10-, and 100-year return periods.

The LANL watersheds are complacent in their pre-fire and post-fire response. Complacent behavior is associated with channel or near-channel source areas. Although an increase in runoff volume is observed, there was no dramatic increase in CNs for Starmer Canyon following the fire. This is an important result because the current application base suggests that the CN increases substantially because reduced vegetative cover and infiltration. This was not observed at LANL.

Large changes in peakflow rates were observed for Starmer Canyon and the Los Alamos area in general following the fire. The increase in runoff volume is partly responsible for the increase in peakflows. Another difference is the hydrograph duration with the post-fire hydrographs having durations on the order of the rainfall event whereas pre-fire; these hydrographs were several hours longer than the event. The increased runoff can rapidly cut into the pre-fire channel areas providing a smoother surface and allowing flow to concentrate more rapidly. This conclusion is consistent with the complacent behavior of this watershed.

Forest fires have occurred with increase frequency in the western U. S. in the last few years especially with the regional drought that has been prevalent during this time. It is important to develop the tools to address post-fire hydrologic behavior, and only through observations such as those reported here will hydrologists be able to provide reliable predictions of fire effects.

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