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Post-fire, rainfall intensity–peak discharge relations for three mountainous watersheds in the western USA

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Abstract:

Wildfire alters the hydrologic response of watersheds, including the peak discharges resulting from subsequent rainfall. Improving predictions of the magnitude of flooding that follows wildfire is needed because of the increase in human population at risk in the wildland–urban interface. Because this wildland–urban interface is typically in mountainous terrain, we investigated rainfall-runoff relations by measuring the maximum 30 min rainfall intensity and the unit-area peak discharge (peak discharge divided by the area burned) in three mountainous watersheds (17–26·8 km^2) after a wildfire.

We found rainfall-runoff relations that relate the unit-area peak discharges to the maximum 30 min rainfall intensities by a power law. These rainfall-runoff relations appear to have a threshold value for the maximum 30 min rainfall intensity (around 10 mm h^{-1}) such that, above this threshold, the magnitude of the flood peaks increases more rapidly with increases in intensity. This rainfall intensity could be used to set threshold limits in rain gauges that are part of an early-warning flood system after wildfire. The maximum unit-area peak discharges from these three burned watersheds ranged from 3·2 to 50 m^3 s^{-1} km^{-2}. These values could provide initial estimates of the upper limits of runoff that can be used to predict floods after wildfires in mountainous terrain. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS wildfire; rainfall; runoff; rainfall intensity; peak discharge

INTRODUCTION

Wildfire is a natural disturbance that can change the biotic and abiotic characteristics of a watershed such that the subsequent hydrologic response to the normal precipitation regime is often a sudden and dramatic increase in water discharge. Wildfires alter the live and dead vegetation in a watershed by: (1) decreasing the canopy interception, which increases the percentage of rainfall available for runoff; (2) decreasing the water normally lost as evapotranspiration, which increases the base flow; (3) consuming ground cover, litter, duff, and debris, which increases runoff velocities and reduces interception and storage. Wildfires also alter the chemical (Debano *et al*., 1977; Giovannini and Lucchesi, 1983) and physical (Doehring, 1968; Wells, 1981; Giovannini *et al*., 1988) properties of the soil that affect infiltration and, thus, the hydrologic response. Changes in annual runoff or changes in peak discharge can be used to quantify this hydrologic response after wildfire.

Changes in the annual runoff caused by various types of deforestation, including fire, have been evaluated using the paired-watershed and the calibrated-watershed methods. The paired-watershed method (e.g. Bates and Henry, 1928; Wilm, 1943; Hibbert, 1967; Anderson, 1974) was used in studies of the effects of clear cutting on annual runoff. Paired-watershed studies also have been used extensively to investigate the effects of prescribed fires as a method of increasing runoff in South Africa (e.g. Rycroft, 1947; Bosch *et al*., 1984, 1986; Lindley *et al*., 1988; Scott, 1993), in Australia (O'Loughlin *et al*., 1982; Ronan, 1986), and in Europe (Soler

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et al., 1994; Soto *et al*., 1994). This method is used to develop a runoff relation between two watersheds (an experimental watershed and a control watershed) before experimental treatment. The method works well if the precipitation regime is uniform over a broad region. In contrast, the calibrated-watershed method develops an empirical equation to predict the runoff relation for a single watershed based on one or more meteorologic, topographic, geologic, and hydrologic factors (e.g. Anderson and Trobitz, 1949; Settergren, 1969; Scott, 1993; Sayeeduzzaman and Weirich, 1996; McCaughey *et al*., 1997). This method has been applied at the hillslope scale in northern California (Rowe, 1948), in South Africa (Scott, 1993), in Spain (Soler *et al*., 1994; Soto *et al*., 1994), and in Israel (Kutiel *et al*., 1995).

The hydrologic effects of wildfire cannot be studied using the paired-watershed and calibrated-watershed methods because pre-fire data are not available except in a few serendipitous cases, where watersheds that were being monitored for other purposes were burned by a wildfire. Cases like this have occurred: (1) in the San Dimas Experimental Forest in southern California, where there was a 2·3-fold increase in annual runoff during the first year after a wildfire and an average of 0·3-fold increase for the next 5 years (Hoyt and Troxell, 1934); (2) in the Entiat Experimental Forest in Washington, which had two- to three-fold post-fire increase over 7 years (Helvey, 1980); (3) in the Custer State Park in South Dakota, where the post-fire annual mean flow decreased 0·50-fold the first year then showed a 0·09- to 2·3-fold increase during the next 6 years (Dan Driscoll, US Geological Survey, personal communication, 1996); and (4) in the highland eucalyptus forests of Australia, where the average annual runoff showed an unusual 0·13 to 0·31-fold decrease (Langford, 1976).

For wildfires other than these serendipitous cases, researchers have used another type of paired-watershed method, where one watershed is burned and another nearby watershed is unburned. Because the two watersheds are not identical, the studies must collect data on the post-fire effects of multiple precipitation events to resolve any differences statistically. Using this method, the responses for mountainous regions of Arizona (Campbell *et al*., 1977) and Wyoming (Troendle and Bevenger, 1996) showed 4·5- and 1·3-fold increases, respectively. The response in annual runoff on the Bega Batholith in Australia (Mackay and Cornish, 1982) was a 3·0-fold increase the first year and a 2·3-fold increase the second year.

Changes in peak discharges can be compared between watersheds if they are expressed as the unit-area peak discharge (peak discharge divided by the burned drainage area). Rowe *et al*. (1954) have suggested that the unit-area peak discharge is perhaps the most sensitive hydrologic indicator of watershed response after wildfire, especially in regions dominated by short-duration, high-intensity rainfall. They investigated the ratio of unit-area peak discharges before and after wildfires in southern California. Their results indicate that for the first year after the wildfire, the ratio increases from two- to three-fold for less frequent, large magnitude storms (100 to 5 year recurrence intervals), from three- to 30-fold for moderate storms (5 to 0·1 year recurrence interval), and from 30- to 40-fold for the most frequent, small-magnitude storms ($<$0·1 year recurrence interval). These results are supported by the observations of Pase and Ingebo (1965), who noted that streamflow that was intermittent during the summer before a wildfire (1% total runoff) was continuous ($\sim$30% total runoff) after a wildfire, and by Harr (1976), who noted a significant reduction in the number of low-flow days. In addition, both Helvey (1980, Fig. 6) and Troendle and Bevenger (1996, Fig. 7) also detected smaller percent increases for less frequent, large-magnitude storms and larger percent increases for more frequent, small-magnitude storms. The sensitivity of peak discharges as a measure of hydrologic response is reflected in the large changes measured by researchers. Hoyt and Troxell (1934) normalized the maximum unit-area discharge for the year by the daily-mean discharge and measured a 6·5-fold increase after a wildfire in a southern California forest. Anderson (1974) observed a 1·45-fold increase in the annual peak discharge in a coastal Oregon forest, and Bolin and Ward (1987) found a 160-fold increase. Some of the largest changes in peak discharge (20- to 870-fold increases) have been reported from the San Dimas Experimental Forest in southern California, (San Dimas, 1954; Sinclair and Hamilton; 1955; Krammes and Rice, 1963).

In summary, measurements of post-fire changes in peak discharge (1·45-fold to 870-fold increase) are much larger than measurements of post-fire changes in annual runoff (0·5-fold decrease to a 4·5-fold increase). Peak discharge is also directly related to flood damage, so that it is important to understand the relation between rainfall and peak discharge. However, changes in peak discharges related to wildfires usually cannot be investigated using the paired-watershed and calibrated-watershed methods because no pre-fire data exist. Post-fire studies using burned and unburned paired watersheds require large amounts of data to overcome statistically the uncertainty inherent in the fact that two watersheds are never identical and that the spatial variability of rainfall will probably cause the watersheds to receive different rainfall intensities, durations, and total accumulations. Wildfires do not change the frequency of rainfall events, but they have been shown to have an effect on the frequency and magnitude of peak discharge events. Thus, this paper focuses on determining post-fire rainfall-runoff relations for unit-area peak discharge from several burned, mountainous watersheds and how this relation changes with time. These relations can be used in the future to predict the magnitude of floods after wildfires from other similar mountainous watersheds.

METHODS

Rainfall intensity can be defined in many different ways. We chose the maximum 30 min rainfall intensity I_{30}, because: (1) rainfall frequency studies (Hershfield, 1961; Miller *et al.*, 1973) indicate in mountainous terrain that 79% of the 1 h rainfall occurs in 30 min; (2) this type of storm has a short duration, lasting between 10 and 60 min; (3) using a minimum sampling interval of 5 to 15 min, the maximum 30 min rainfall intensity would be based on at least two measurements; and (4) some historic data exist for maximum 30 min rainfall intensities. Therefore, the relation between unit-area peak discharge Q_u and maximum 30 min rainfall intensity I_{30} was investigated for three wildfires that had burned watersheds in mountainous terrain in South Dakota, Colorado, and New Mexico (Figure 1): (1) the Galena fire burned almost 6900 ha in the Black Hills near Rapid City, South Dakota, during July 1988 (Whitesides, 1989); (2) the Buffalo Creek fire burned about 4690 ha in the Front Range southwest of Denver, Colorado, during May 1996 (Moody and Martin, 2001a,b); and (3) the Cerro Grande fire burned 17 300 ha across the Jemez Mountains near and in Los Alamos, New Mexico, during May and June 2000 (BAER, 2000). In each case, no pre-fire data were available to use the paired- or calibrated-methods, so that the scope of these investigations was limited to the post-fire period and to one watershed from each burned area.

A severely burned watershed was selected within each fire perimeter (Figure 1). Both Bear Gulch and Spring Creek had some flow after the wildfires, so the US Geological Survey installed stream gauges near the middle of the Bear Gulch watershed and near the mouth of Spring Creek watershed. In Bear Gulch, 100% of the drainage area upstream from the stream gauge was severely burned (Whitesides, 1989) and in Spring Creek 79% was classified as severely burned (Bruggink *et al.*, 1998; Table I). Because the stream gauges malfunctioned during some large flood events, indirect discharge measurements were required to determine the peak discharge of these floods in Bear Gulch and Spring Creek. Upper Rendija Canyon remained an ephemeral stream after the wildfire, so no stream gauge was installed. Instead, 22 cross-sections were surveyed soon after the wildfire (June 2000) to provide a basis for indirect discharge measurements in subwatersheds within Upper Rendija Canyon. These subwatersheds ranged in size from 0·25 to 5·07 km^2 and all were severely burned (BAER, 2000).

Two rain gauges were deployed in the Bear Gulch and Spring Creek watersheds and a rain-gauge network was deployed in the Rendija Canyon watershed after the wildfires (Figure 1). In the Bear Gulch and Spring Creek watersheds, one gauge was deployed near the mouth, at the stream gauge site, and one near the watershed divide. The rain gauges in Bear Gulch recorded cumulative rainfall on analog charts; the traces were digitized in approximately 10 min intervals and at break points on the trace. The rain gauges in Spring Creek were the tipping-bucket type (capacity 0·25 mm per tip) interfaced with a data logger that recorded 5 min rainfall accumulations. Data were transmitted at 15 min intervals *via* satellite unless the rain intensity exceeded a pre-set threshold, and then the data were transmitted at 5 min intervals. A network of 11 tipping-bucket rain gauges (which recorded the time of each tip equal to 0·25 mm) was deployed in Upper Rendija Canyon (Figure 1).

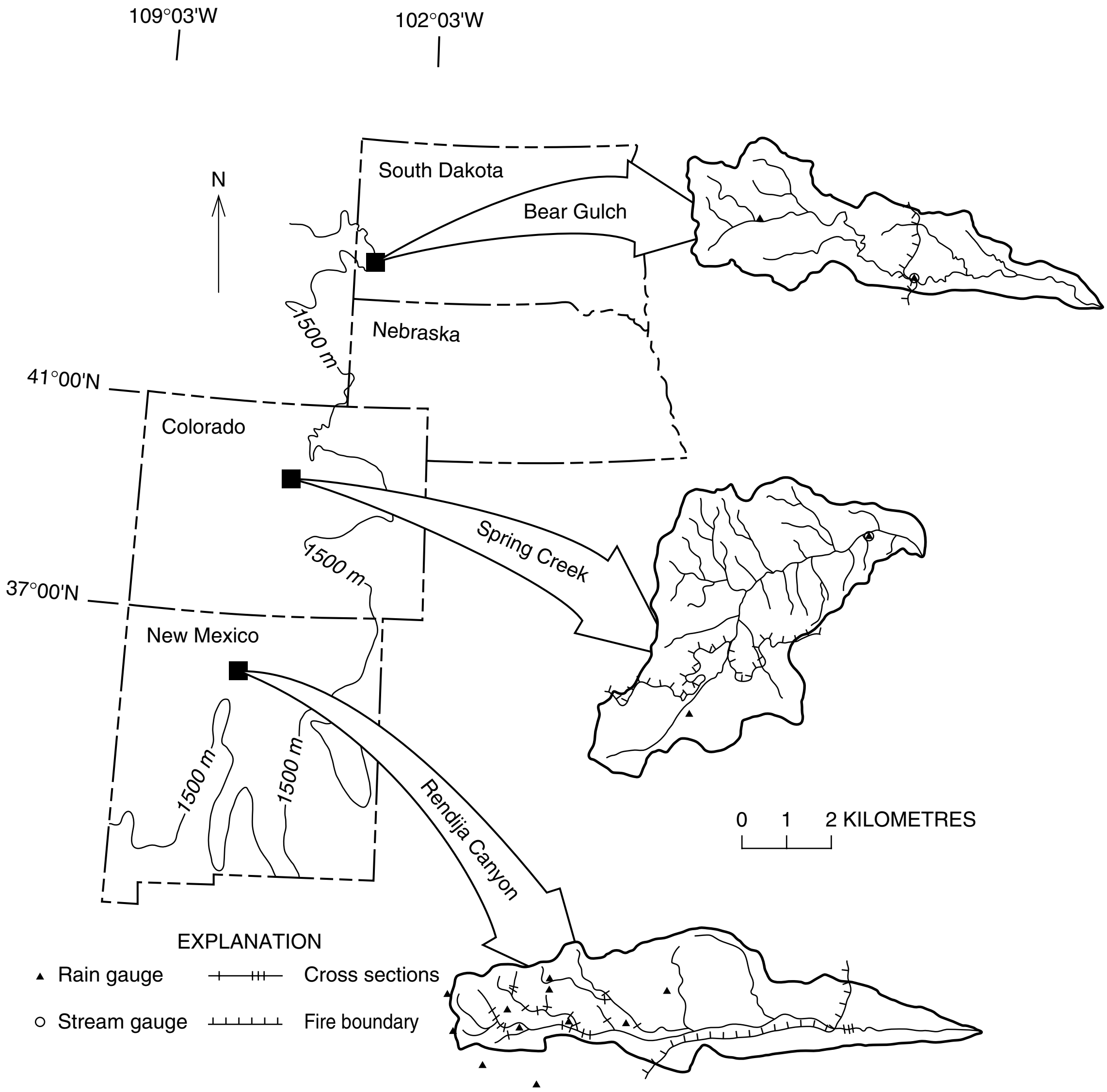

Figure 1. Location of three burned watersheds in mountainous terrain relative to the 1500 m topographic elevation. The hatch lines on the fire boundary point in the direction of the burned area. The total drainage area for Bear Gulch is 17 km^2, for Spring Creek it is 26·8 km^2, and for Rendija Canyon it is 24·8 km^2

In Bear Gulch and Spring Creek, I_{30} values were measured for multiple rainstorms, and the corresponding unit-area peak discharges were measured at one location. I_{30} was calculated for all rain events at the two rain-gauge sites during the summer months (June through September) over a period of 3–5 years after the wildfire and then averaged to reduce the spatial variability. The corresponding unit-area peak discharge for Bear Gulch and Spring Creek was equal to the instantaneous discharge (above a baseline discharge estimated before the runoff event) divided by the area burned.

In Rendija Canyon, only 4 months of data were available. Two rainstorms occurred in early July 2000, and the I_{30} was calculated for each rain gauge in the network of 11 gauges. Using the spatial data provided by the rain-gauge network, the rainfall intensities for each subwatershed were calculated as area-weighted averages.

Table I. Characteristics of the burned watersheds

Burned watershed	Drainage area		Elevation of mouth (m)	Relief ratio	30 min rainfall intensity[a] (mm h^{-1})			Rain gauge separation (km)	Period of record considered
	Total (km^2)	Burned (%)			1 year	10 year	100 year		
Bear Gulch	17	65	1100	0·049	32	70	106	8	1989–1991
Spring Creek	26·8	79	1880	0·047	22	56	88	10	1997–2000
Rendija Canyon	24·8	78	1920	0·065	20	48	76	0·3–1·5	Summer 2000
Rendija Canyon subwatersheds	0·25 to 5·07	100	2160	>0·2	20	48	76		

[a]Isopluvials were interpolated on 30 min rainfall maps published by Hershfield (1961).

Based on the spatial pattern of rainfall intensities, the indirect discharge measurements for each subwatershed could be associated with one of two storms that occurred after the initial survey in June 2000 but before the indirect discharge measurements in July 2000. Unit-area peak discharge was calculated by using an indirect method (Dalrymple and Benson, 1967) at multiple cross-sections in 15 subwatersheds after these storms. A value of Manning's roughness coefficient was calculated from velocity and depth measurements made on July 18, 2000, during a small flash flood at one of these cross-sections. At other cross-sections, Manning's roughness was calculated using the Cowan (1956) method and Jarrett's (1984) empirical equation. Where significant erosion or deposition had occurred, the original cross-section profiles measured in June 2000 were used with the high-water marks surveyed in July 2000 to compute the area, depth, slope, and discharge. Relief ratios for each watershed were calculated from measurements made on 7·5′ topographic maps. The ratios were calculated as the difference in elevation of the highest point near the headwaters of the main channel minus the elevation of the lowest point at the mouth of the drainage divided by the channel length between these two points.

RESULTS

The unit-area peak discharge ranged over six orders of magnitude, depending upon the rainfall intensity. In Bear Gulch, the maximum unit-area peak discharge Q_u was 3·2 m^3 s^{-1} km^{-2} for a rainfall intensity that had a recurrence interval of about 10 years (Figure 2A, Table I). The rainfall-runoff relation between I_{30} and Q_u approximates a power law with possibly two different exponents (or two slopes on a log–log plot), depending upon whether the I_{30} is greater than or less than about 10 mm h^{-1}. The change in slope at approximately 10 mm h^{-1} appears more clearly in the Spring Creek data set, where the maximum Q_u was 24 m^3 s^{-1} km^{-2} for a rainfall intensity that had a recurrence interval of about 100 years (Figure 2B). In Rendija Canyon, the rainfall-runoff relation also appears to approximate a power law (Figure 3C) and the maximum Q_u was about 50 m^3 s^{-1} km^{-2} for rainfall intensities less than the 2 year recurrence interval (30 mm h^{-1}). These limited data also suggest a change in slope, but perhaps at slightly higher value of I_{30} ($\sim$11 mm h^{-1}) than in either Bear Gulch or Spring Creek.

DISCUSSION

Rainfall variability

The variability of the data sets shown in Figure 2 probably reflects the variability of the rainfall intensities more than the uncertainty in the discharge measurements. Convective thunderstorms are known to have sharp

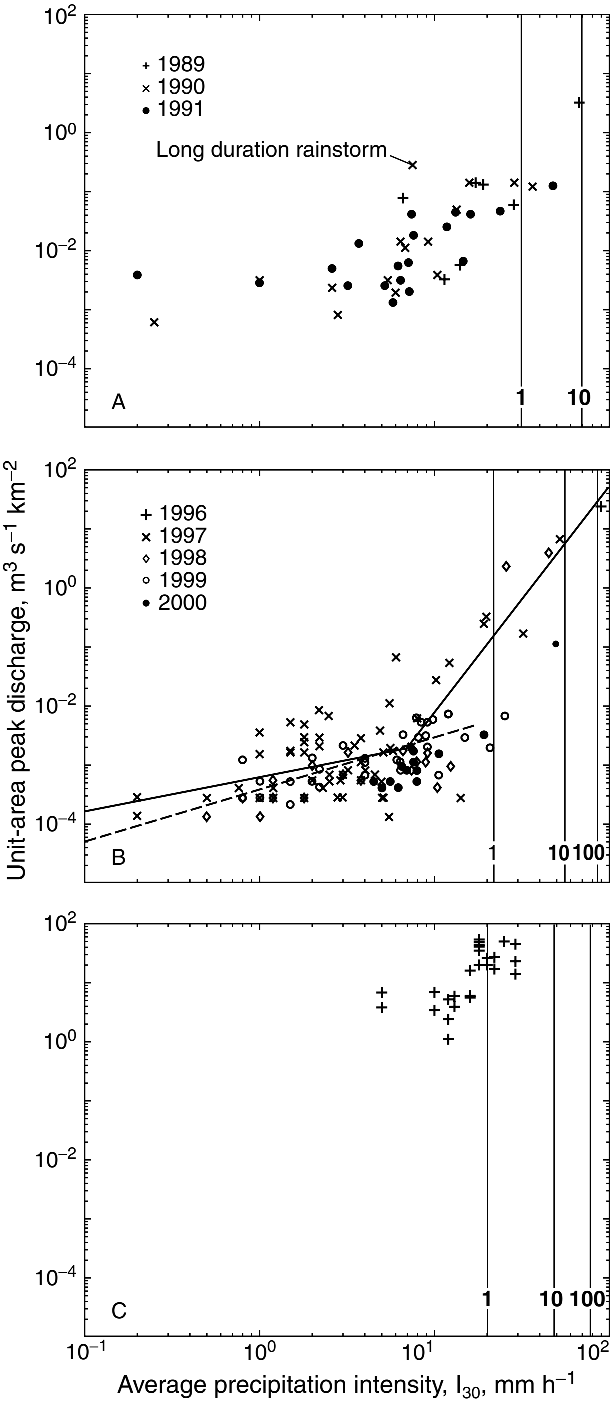

Figure 2. Rainfall-runoff relation for (A) Bear Gulch, (B) Spring Creek (solid line is for 1996–97 and dashed line is for 1999), and (C) subwatersheds within the upper half of Rendija Canyon. The vertical lines indicate the maximum 30 min rainfall intensities for the 1 year, 10 year, and 100 year recurrence interval based on a rainfall frequency atlas (Hershfield, 1961)

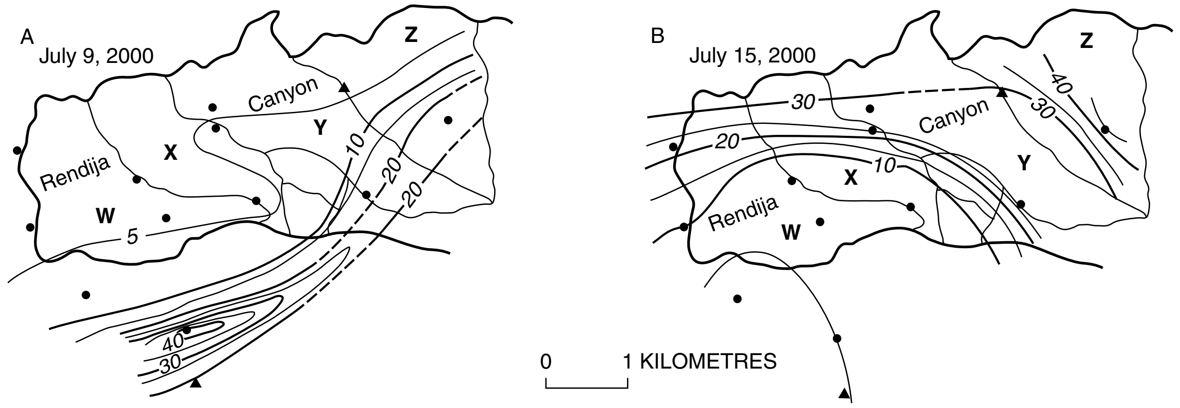

Figure 3. Spatial variability of maximum 30 min rainfall intensities (mm h^{-1}) in the upper part of Rendija Canyon for two dates in July 2000. The solid circles and triangles indicate the location of rain gauges (see also Figure 1). The letters W, X, Y, and Z label subwatersheds

gradients in rainfall and rainfall intensities (Jarrett, 2001) and to vary in size so that entire watersheds are not necessarily subjected to the same rainfall intensities. Such spatial variability is easily seen in Rendija Canyon where a network of rain gauges was deployed (Figure 3). For example, subwatersheds X in Upper Rendija Canyon received less than 10 mm h^{-1} from the July 9, 2000, storm (Figure 3A) but had a sharp gradient across it during the July 16, 2000, storm (Figure 3B), with maximum intensities estimated to be above 30 mm h^{-1}. Subwatershed Y experienced a weak gradient on July 9, but had a nearly uniform rainfall between 20 and 30 mm h^{-1} during the July 16 event.

The variability of the rainfall intensities computed for the two rain gauges in Spring Creek is greater than that for the two rain gauges in Bear Gulch (Figure 4). This may be a function of the greater distance between rain gauges in Spring Creek (Table I) or it may be because more low-intensity rainfall events were measured in Spring Creek than in Bear Gulch. These lower-intensity rainfall events show more variability between the two rain gauges (Figure 4), which suggests the area of the rainfall may be smaller than the spacing between the two rain gauges. The higher-intensity rainfall events have less variability between the two rain gauges, which may indicate that the area of the rainfall is larger, or at least as large as the spacing between the two rain gauges.

Watershed differences

The unit-area peak discharges of the watersheds in Rendija Canyon were greater than those measured either in Bear Gulch or Spring Creek (Figure 5). Rainfall with intensities less than about 10 mm h^{-1} certainly occurred in Rendija Canyon, but very little discharge data were collected because no stream gauges were deployed and no indirect measurements were made. A reason for the difference in magnitude of the response between Rendija Canyon and Bear Gulch and Spring Creek may be the effect of storm size relative to watershed size. If some of the rainstorms were smaller than the drainage area measured by the stream gauges in Bear Gulch (11 km^2) and Spring Creek (21 km^2), then the calculated unit-area peak discharge would be less than the actual unit-area peak discharge. Based on the spatial variability of rainfall described above, low-intensity storms may be smaller in size than high-intensity storms, so that this effect would be most pronounced for the lower rainfall intensities. The unit-area peak discharges for Bear Gulch and Spring Creek are, therefore, probably minimal estimates.

Another difference between Rendija Canyon and the other two sites is that the relief ratio in Rendija Canyon is greater than in either Bear Gulch or Spring Creek (Table I). The subwatersheds in Rendija Canyon with low-order channels have relief ratios $\geq 0{\cdot}2$. This suggests little area existed adjacent to the channels for runoff storage, which was confirmed by field observations. Interestingly, in two higher-order channels of Upper Rendija Canyon, the discharge decreased downstream from about 50 m^3 s^{-1} to about 10 m^3 s^{-1} over a

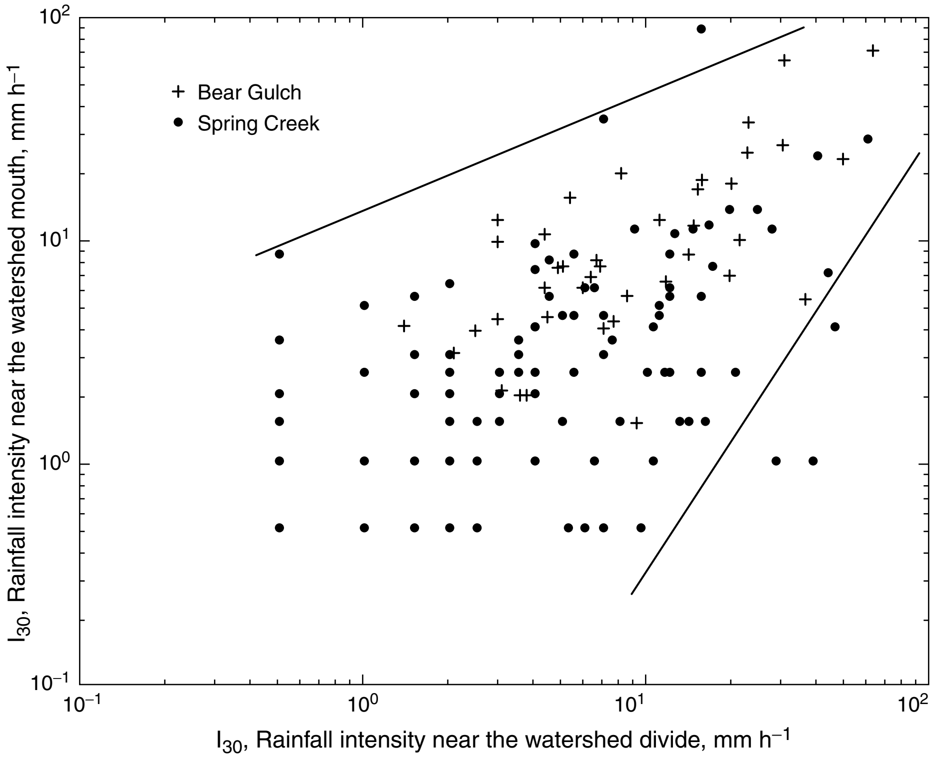

Figure 4. Comparison of maximum 30 min rainfall intensities for rain gauges located near the watershed divides and near the watershed mouths in Bear Gulch and Spring Creek. The two lines have been drawn by eye simply to indicate the general decrease in the variability of the data as the maximum 30 min rainfall intensity increases

distance of about 2000 m. This decrease may be the result of eroded sediment settling out of suspension on the falling limb of the hydrograph, creating a new bed up to 1 m thick in some reaches, which trapped and stored water similar to a situation observed in the Grand Canyon (Eleanor Griffin, USGS, personal communication, 2001). However, most of the data points represent steep, low-order subwatersheds that have greater unit-area peak discharge than less steep watersheds.

Threshold

The change in slope of the rainfall-runoff relations (Figure 2) suggests that, for burned watersheds, a threshold of rainfall intensity exists that implies a critical change in the behaviour of the hydrologic response. This threshold for Spring Creek was estimated to be 10 mm h^{-1}, and two rainfall-runoff relations were determined by linear regressions of the combined (1996 and 1997) log-transformed data (Table II). A similar analysis was done for the combined Bear Gulch data (1989, 1990, and 1990) using a threshold of 10 mm h^{-1}, and for the Rendija Canyon data using a threshold of 11 mm h^{-1}. The rainfall-runoff relations have the form $Q_u = aI_{30}^b$ and the exponent b of the power law is different above and below the threshold (Table II). The change in value of the exponent of the power law supports the existence of a physical threshold. Relatively large confidence limits reflect the limited number of storms each year. Some data from the Barrett (Sinclair and Hamilton, 1955) and Johnstone Peak fires (Krammes and Rice, 1963; Doehring, 1968) in the San Gabriel Mountains of Southern California, where the terrain is also steep and granitic but the vegetation is predominately chaparral, indicate a similar rainfall-runoff relation for >10 mm h^{-1} (Figure 5). A threshold intensity was also reported by Mackay and Cornish (1982) for watersheds on the Bega Batholith in New South Wales.

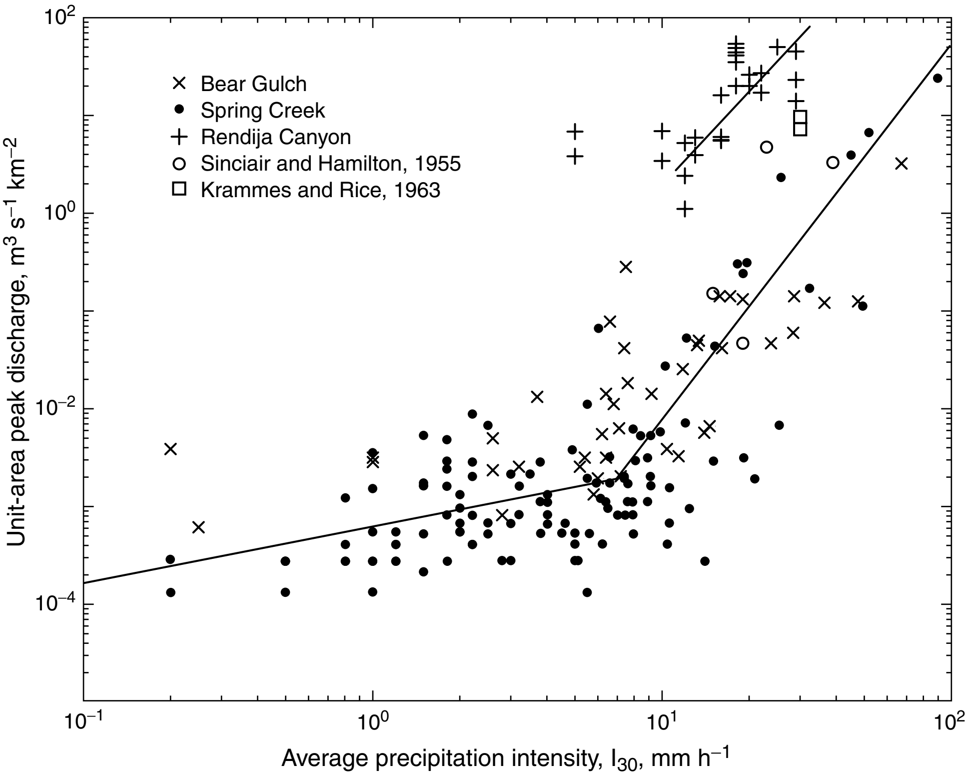

Figure 5. Rainfall-runoff relation for severely burned watersheds. The solid lines through the data represents the linear regression of the data for 1996 and 1997 in Spring Creek and for the summer of 2000 in Rendija Canyon

Table II. Rainfall-runoff relations, $Q_u = aI_{30}^b$, for three burned watersheds

Watershed	Range of I_{30} (mm h^{-1})	a	b	95%CI[a]	r^2
Bear Gulch, 1989, 90, 91	<10	2.5×10^{-3}	0·60	0·57	0·19
	>10	3.8×10^{-5}	2·4	1·0	0·62
Spring Creek, 1996, 97	<10	6.6×10^{-4}	0·59	0·37	0·16
	>10	1.2×10^{-6}	3·8	3·6	0·66
Spring Creek 1999	<16	4.3×10^{-4}	0·91	0·34	0·53
	>16		Insufficient data		
Rendija Canyon, Summer 2000	<11		Insufficient data		
	>11	4.4×10^{-3}	2·8	1·3	0·49

[a]95% CI = 95% confidence limits on the exponent b.

One reason for the existence of a critical threshold intensity could be the infiltration rate into the hillslopes. Infiltration rates have been shown to decrease by a factor of two to seven after wildfires (Cerdà, 1998; Martin and Moody, 2001) so that post-fire rainfall intensities that exceed this infiltration rate and cause runoff may be lower than the pre-fire intensities required to produce comparable runoff. Below approximately 10 mm h^{-1} the rainfall intensity may be below the watershed average infiltration rate, such that a majority of the rainfall infiltrates, with some transient runoff (Ronan, 1986), and some subsurface flow, which may cause either quickflow (Hewlett and Hibbert, 1967) into the channel or a lagged response. Above 10 mm h^{-1} the rainfall intensity may exceed the average watershed infiltration rate, such that the runoff is dominated by sheetflow, which produces flash floods. For example, if the rainfall intensity is 20 mm h^{-1} (approximately the 1 year recurrence interval for these watersheds), then the unit-area peak discharge response would be 27 times greater than the response would have been if the rainfall-runoff relation did not change at the threshold of 10 mm h^{-1}. If the rainfall intensity is 55 mm h^{-1} (approximately the 10 year recurrence interval for these watersheds), the response would be 700 times greater.

A second reason for the existence of a critical threshold intensity could be the nature of the hillslope friction, which controls overland flow velocities. Overland flow on steep mountainous terrain can be characterized as shallow flow with large relative roughness (ratio of bed-roughness height to flow depth). Recent studies have shown that, for partial inundation of the bed roughness, the frictional resistance increases with an increase in flow depth (Lawrence, 1997; Nikora *et al.*, 2001). This dependence is different than previous formulations of frictional resistance, which assumed a Manning's or Chezy parameterization where the frictional resistance decreases with an increase in flow depth (Moore and Foster, 1990). After complete inundation of the bed roughness, the frictional resistance decreases with increases in flow depth. This change in behaviour of the frictional resistance implies the existence of a critical threshold, i.e. there should be a dramatic increase in runoff velocities when rainfall intensities are large enough to cause the runoff to cover completely the characteristic bed roughness of the hillslope. At this threshold of complete inundation, the discharges per unit width may change from being proportional to $h^{0\cdot5}$ to being proportional to h^2, which would cause a sudden increase in the discharge from the hillslope.

Some evidence indicates that this threshold may change with time, perhaps approaching the pre-fire thresholds. In the Spring Creek watershed, several events in 1999 and 2000, corresponding to intensities slightly greater than 10 mm h^{-1}, produced unit-area peak discharges less than those in 1997 and 1998. Visual examination of Figure 2B indicates that the change in slope at the threshold appears to have shifted from about 10 mm h^{-1} in 1996–97 to about 16 mm h^{-1} in 1999 (open circles in Figure 2B near the line for the 1 year recurrence interval). But the slope or exponent of the power law ($0\cdot91 \pm 0\cdot34$) remained essentially the same as the exponent ($0\cdot59 \pm 0\cdot37$) for the 1996–97 data. This shift with time may reflect the recovery of the hillslopes as infiltration and the canopy density of the fire-adapted, under-story vegetation increase. It also may explain the decrease in extreme floods in 1999 and 2000 (Moody and Martin, 2001a,b). This decrease was greater for the more frequent, lower rainfall intensities than for the less frequent, higher rainfall intensities, similar to the effect observed by Rowe *et al.* (1954) for the southern California mountains. For example, in 1997, an I_{30} of about 19 mm h^{-1} ($\sim$1 year recurrence interval, Table I) produced a Q_u of 0·31 m^3 s^{-1} km^{-2}, whereas in 2000 a similar intensity produced a Q_u of only 0·0031 m^3 s^{-1} km^{-2}, corresponding to a 100-fold decrease. Also in 1997, an I_{30} of about 50 mm h^{-1} ($\sim$ 10 year recurrence interval, Table I) produced a Q_u of 6·6 m^3 s^{-1} km^{-2}, whereas in 2000 a comparable intensity had produced a Q_u of only 0·11 m^3 s^{-1} km^{-2}, or a 60-fold decrease (Moody and Martin, 2001a).

CONCLUSIONS

The literature review indicates that, after a wildfire, changes in peak discharges are larger than changes in annual runoff and are, therefore, more sensitive measures of hydrologic response. Based on data collected from three burned mountainous watersheds, rainfall-runoff relations exist that relate the unit-area peak discharge to the maximum 30 min rainfall intensity by a power law. The change in the unit-area peak discharge is greater for the more frequent, lower-intensity rainfall events than for the less frequent, higher-intensity rainfall events. The rainfall-runoff relations appear to have a threshold value for the maximum 30 min rainfall intensity (around 10 mm h^{-1}), such that above this threshold the magnitude of flood peaks increases more rapidly. Estimates of this threshold are limited by the number of storms each year and by the fact that this threshold may be changing with time during the transient period after a wildfire. This threshold of rainfall intensity could be used to set threshold limits in rain gauges that are part of an early-warning flood system after wildfire. The maximum unit-area peak discharges from these three burned watersheds ranged from 3·2 to 50 m^3 s^{-1} km^2. These values could provide initial estimates of the upper limits of runoff that can be used to predict floods after wildfires in mountainous terrain.

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