Gully Erosion after Wildfire

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Abstract

Predicting runoff and erosion from watersheds burned by wildfires requires an understanding of the spatial structure of both hillslope and channel drainage networks. We investigate the small-scale and large-scale structures of drainage networks using field studies and computer analysis of 30-m digital elevation model. Topologic variables were derived from a composite 30-m DEM, which included 14 order 6 watersheds within the same geological terrain (Pikes Peak batholith). Both topologic and hydraulic variables were measured in the field in two burned watersheds (3.7 and 7.0 hectares) located within one of the order 6 watersheds burned by the 1996 Buffalo Creek Fire.

Horton ratios of topologic variables (stream number, drainage area, stream length, and stream slope) for small-scale and large-scale watersheds are shown to scale geometrically with stream order (i.e., to be scale invariant). Hydraulic variables (width, depth, cross-sectional area, and bed roughness) for small-scale watersheds also were found to be scale invariant across 3 to 4 stream orders. Bed roughness and width-to-depth ratio were constant across all scales. Fewer order 1 and order 2 streams were observed in the field than predicted by theory. The different hillslope drainage network pattern, composed of multiple parallel rills or multiple converging rills, may replace some order 1 streams. This reduction in the number of order 1 and 2 streams appears to be a consequence of hillslope processes.

Key words: channel network, hillslope network, wildfire, gullies, scaling

1.0 Introduction

Wildfires are landscape disturbances that change the hydrologic response of watersheds. When substantial rainfall follows a wildfire, the subsequent runoff and erosion can extend the existing pre-fire channel network farther up the hillslope. With an increase in wildfire throughout wildland-urban interface areas in the western United States and elsewhere, a need exists to model burned hillslope and channel systems in order to predict floods and subsequent erosion from burned watersheds. One fundamental question related to this erosion is how the channel network structure of this newly incised terrain is similar to or different from the network as a whole. If the channels follow previously defined, but unchannelized drainages, then it is possible that the larger drainage pattern is preserved during the new period of erosion and incision. However, it is also possible that new hillslope rills and gullies may define a new drainage network with a different structure particularly at the hillslope-channel interface. Full-scale 3-D numerical models of entire watersheds are impractical to implement because they require extensive site-specific topographic input and are limited to a single-thread reach of a channel rather than channel networks with numerous confluences. They are inappropriate because these models are designed to resolve small-scale (0.01-1m) detailed flow and sediment erosional and depositional features within the channel reach and this scale of resolution is unnecessary for predictions of runoff and erosion at the watershed scale. Therefore similarities and scaling properties are needed to simplify runoff and erosion modeling of both hillslope and channel networks.

Initially, the theoretical random model (Shreve, 1966, 1969) suggested that channel networks in a particular lithology or similar geological terrain developed as a random structure with a bifurcation ratio of 4.0. Later theoretical models of channel networks were based on such physical principles of effective connectivity, an empirical power law that relates slope to discharge, and the minimum energy expenditure and dissipation (Howard, 1990; Sun et al., 1994a; Rodriguez-Iturbe and Rinaldo, 1997). These theoretical networks often have a fractal dimension near 2, which indicates the networks are “space filling” and drain a watershed efficiently or with minimum energy expenditure. Sun et al. (1994b) investigated the effect of including a hillslope process threshold to determine theoretical channel networks and later Tucker and Bras (1998) expanded the idea by investigating several different hillslope thresholds. Theoretical models are limited by the resolution of the large-scale digital elevation models (DEMs) and do not resolve small-scale structures at the hillslope-channel interface. A summary by Abrahams (1984) of field studies and an analysis by Peckham (1995) of large river basins suggest that channel networks diverge from a random structure and these investigations have begun to explain channel network structure based on physical principles.

Our purpose in this short paper is to characterize spatially (for modeling applications) the drainage networks of hillslopes and channels in a watershed disturbed by wildfire. We rely on both field studies and computer analysis to 1) examine the small scale (0.01-1.0 km^2) structures of the post-fire hillslope and channel networks, 2) compare them to the structure of channel networks in unburned watersheds derived from computer analysis of large scale (1-1000 km^2) digital elevation models, and 3) explore how the channel network interfaces with the hillslope network.

2.0 Background

In May 1996, the Buffalo Creek Fire burned approximately 50 km^2 in the Pike National Forest southwest of Denver, Colorado. The fire burned two adjacent watersheds, Buffalo Creek and Spring Creek (Figure 1). A larger proportion of the Spring Creek watershed burned, 79% (21.2 km^2), compared with the Buffalo Creek watershed, 21% (25.7 km^2). These watersheds are underlain by the Pikes Peak granite batholith and have soil profiles that include emerging corestones and thick zones of decomposed granite called grüs. Two months after the wildfire,

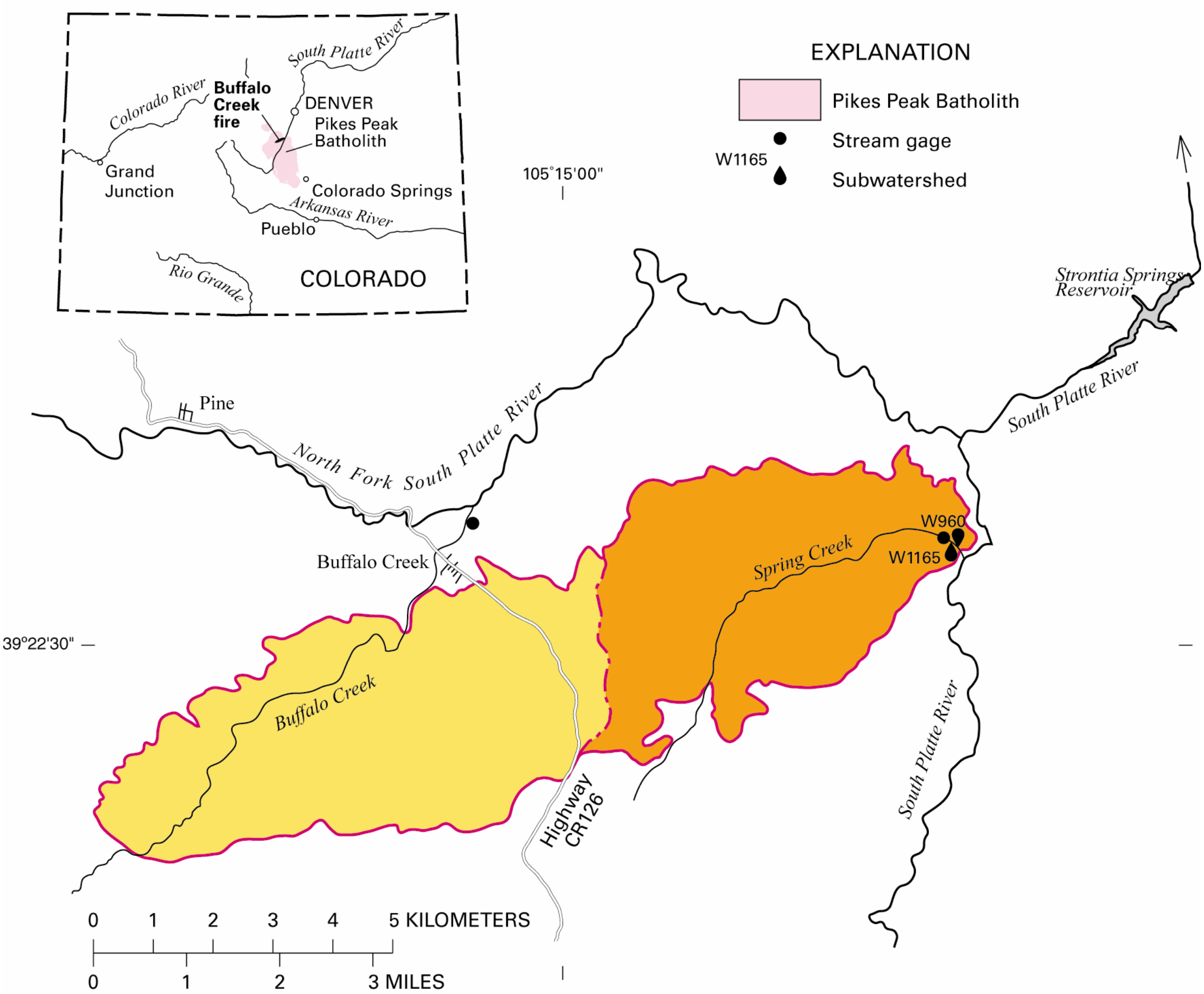

Figure 1. Location of the two burned subwatersheds W960 and W1165 in the Pikes Peak granite batholith and within the Spring Creek watershed.

runoff from a short-duration, high-intensity rainstorm changed the topography of the watersheds. The storm lasted about one hour and the maximum rainfall intensity was ~90 mm h^{-1} (Moody and Martin, 2001a). It removed most of the ash from the hillslopes, rilled the hillslope surfaces, channelized drainages, led to a head-ward extension of the channel network into previously unincised terrain, and deposited sediment on alluvial fans at the mouths of tributaries and in the main channel of Spring Creek (Moody, 2001).

Two subwatersheds, W960 and W1165 (the number equals the distance in meters from the mouth of Spring Creek) were investigated to determine the amount of erosion and the structure of the hillslope and channel drainage networks in this newly incised terrain (Figure 1). Subwatershed W960 (7.01 ha) is a south-facing watershed with an average hillslope length (1/2 x drainage density, Horton, 1945) of 24 m and W1165 (3.71 ha) is a north-facing watershed with an average hillslope length of 10 m.

3.0 Methods

3.1 Small-Scale Measurements

Field measurements of hydraulic variables were made in 1999 at 5-m intervals in all gullies and channels incised into the existing drainage network in watershed W960 and W1165 as well as in some rills. Assuming that the post-flood surface adjacent to the rills, gullies, and channels was the same as the pre-flood surface, the volume of material removed from the recently incised drainages was calculated by extending this post-flood surface across the channel, measuring the depth down from this imaginary surface to the bottom of the incised channel, and multiplying by the average of the top width and bottom width. Identification of the location of the pre-flood surface above the incision was aided in many places by using tree roots left exposed after the floods. These roots and rootlets, typically, were unbroken and in some cases spanned the entire gully or channel. Some topologic variables were measured from digital and photogrametric products. Statistical measures (means, coefficient of variation, skewness, and kurtosis) of the distribution of each topologic and hydraulic variables were computed separately for W960 and W1165 (Table 1).

A Horton ratio is a descriptor of the change in spatial structure of stream variables across scales (stream orders). The Horton ratio of stream variable X, R_X (Table 1 and 2), can be redefined for mathematical convenience as $R_X = \frac{c}{|c|} e^{|c|}$ and then c is the slope of a log-linear plot of the following equation

$$X = ae^{ck} \qquad (1)$$

where a is a constant and k is the scale factor or stream order.

3.2 Large-Scale Measurements

A regional topologic analysis of stream networks was completed using data from 36, 7.5-minute quadrangles joined to create a single composite 30-m DEM that encompassed the topography of much of the Pikes Peak granite batholith. The extent of the batholith was determined from the digital geologic map of Green (1992) projected to match the projection of the composite DEM. The individual DEMs were joined to create the composite 30-m DEM by using the program RiverTools (Peckham, 1998; Rivix Limited Liability Company, 2001), which was also used to analyze the channel network. We used the D-8 flow direction algorithm (O'Callahan and Mark, 1984) and iterative-linking flat resolution (Jenson and Domingue, 1988)

Table 1. Topologic and hydraulic stream variables of subwatersheds W960 and W1165

[--, no data]

		Number of measurements		Mean		Coefficient of variation		Skewness		Kurtosis	
	Order	W960	W1165	W960	W1165	W960	W1165	W960	W1165	W960	W1165
Number of streams	0	--	--	365	378	--	--	--	--	--	--
	1	--	--	13	19	--	--	--	--	--	--
	2	--	--	4	5	--	--	--	--	--	--
	3	--	--	1	2	--	--	--	--	--	--
	4	--	--	--	1	--	--	--	--	--	--
Drainage area (ha)	1	11[a]	18	0.20	0.06	1.20	0.85	2.8	1.6	8.4	2.4
	2	4	4[a]	0.95	0.27	0.69	0.56	--	-1.7	--	2.7
	3	1	2	7.02	0.94	--	0.35	--	--	--	--
	4	--	1	--	3.72	--	--	--	--	--	--
Length (m)	0	36[a]	38[a]	27	29	0.70	0.48	0.3	0.6	-0.1	-1.0
	1	13	18	49	55	0.69	0.56	0.9	0.9	0.1	-0.4
	2	4	5	137	50	0.40	0.57	1.2	0.7	1.9	-2.6
	3	1	2	292	113	--	0.16	--	--	--	--
	4	--	1	--	223	--	--	--	--	--	--
Slope	1	120	172	0.41	0.40	0.24	0.29	0.50	0.20	1.4	-0.4
	2	106	42	0.34	0.35	0.35	0.43	0.78	0.7	1.0	0.8
	3	57	47	0.22	0.30	0.18	0.53	0.16	0.9	-0.8	-0.1
	4	--	41	--	0.22	--	0.64	--	2.7	--	7.4
Width (m)	0	109[b]	--	0.30	--	0.43	--	1.3	--	1.4	--
	1	120	172	0.98	0.55	0.62	0.49	1.6	1.4	3.2	2.5
	2	106	42	1.93	1.06	0.59	0.55	1.6	1.4	3.4	2.8
	3	57	47	5.03	1.44	0.35	0.42	1.1	0.7	2.3	0.2
	4	--	41	--	4.02	--	0.30	--	0.5	--	0.0
Depth (m)	1	120	172	0.20	0.12	0.86	0.64	1.7	1.4	2.7	1.9
	2	106	42	0.42	0.33	0.79	0.80	1.3	1.2	1.5	0.7
	3	57	47	0.86	0.39	0.40	0.64	1.1	1.3	1.5	2.2
	4	--	41	--	0.38	--	0.75	--	0.7	--	-0.8
Cross-sectional area (m^2)	1	120	172	0.19	0.049	1.63	0.92	4.6	3.7	25.8	23.2
	2	106	42	0.69	0.29	1.06	1.00	1.9	0.6	3.9	-0.3
	3	57	46	4.35	0.43	0.79	0.79	3.3	1.5	13.6	2.6
	4	--	41	--	1.33	--	0.72	--	0.8	--	-0.1
Bed z_0=k/10, (mm)	1	120	163	5.5	5.2	0.61	0.69	0.9	1.1	-0.3	1.0
	2	106	36	10.4	11.8	0.64	0.62	1.1	0.6	0.5	-0.3
	3	57	27	4.8	15.9	0.50	1.02	2.4	1.3	7.1	0.6
	4	--	39	--	4.7	--	1.04	--	1.5	--	1.7
Width-to-depth ratio	1	120	172	8.6	7.3	1.20	1.28	2.7	3.8	7.8	16.1
	2	106	42	8.9	5.4	0.52	1.04	5.4	2.5	31.9	6.9
	3	57	47	6.5	5.7	0.40	1.14	0.7	4.0	0.8	20.4
	4	--	41	--	22.2	--	1.09	--	2.8	--	10.1

[a] areas for 1 or 2 streams were unavailable

[b] subsample of all the rills

in order to determine flow directions on the DEM. Streams were differentiated from surrounding hillslopes by using a threshold contributing area of 0.01 km^2 (1 ha). This area is consistent with an average contributing area shown by Montgomery and Dietrich (1994, Figure 11.9) for a channel slope equal to the average channel slope for W960 and W1165 and is on the order of the size of the study watersheds. Field evidence indicates that little, if any, channel incision existed within the study watersheds before the flooding events.

After delineating the stream network for the composite 30-m DEM, large-scale measurements of topologic variables (bifurcation, drainage area, length, and slope) were derived from the DEM only for those watersheds that were within the batholith. Spring Creek was an order 6 watershed, so large-scale measurements were derived for 14 order 6 watersheds within the batholith for comparison with the small-scale data.

4.0 Results

Numerous hydraulic measurements were made for each stream order in the small-scale W960 and W1165 subwatersheds, which provide information on the probability distribution of each topologic and hydraulic variable. All of the distributions are positively skewed except for the drainage area for the order 2 streams in W1165. Similarly, the negative kurtosis (flatness of the distribution) is relatively small (<-2.6), while the positive kurtosis (peakedness of the distribution) has a wide range from 0.01 to greater than 20 for cross-sectional area and width-to-depth ratio for some stream orders. Mean width-to-depth ratios at individual cross sections ranged from 5-9 for order 1, 2, and 3 streams, values typical of rills and gullies. This ratio for individual cross sections changed abruptly to about 20 for the order 4 stream in W1165, a value typical of channels.

4.1 Channel Network

The Horton ratios for bifurcation, drainage area, and stream length (R_B, R_A, and R_L) were computed for 14 watersheds in the 30-m DEM (Table 2). The coefficient of determinations (r^2) for fitting equation (1) were equal to 1.00. These ratios are close to those ratios published by

Table 2. Horton ratios for different spatial scales

[na, not available; negative sign indicates variable decreases as stream orders increases]

Variable	Kentucky River order 8	Powder River order 8	Pikes Peak batholith 14 watersheds order 6	W960 order 3	W1165 order 4
			Topologic variables		
Bifurcation	4.6	4.7	4.3	3.6	2.6
Drainage area	4.7	5.0	4.8	5.9	3.8
Length	2.5	2.4	2.2	2.5	1.6
Slope	na	na	-1.4	-1.4	-1.2
			Hydraulic variables		
Width	na	na	na	2.3	1.9
Depth	na	na	na	2.1	1.4
Cross-sectional area	na	na	na	5.0	2.7
Bed roughness	na	na	na	-1.1	-1.0
Width-to-depth ratio	na	na	na	-1.2	1.4
Percent total net erosion	na	na	na	3.2	1.8

Peckham (1995) for the "humid" order 8 Kentucky River watershed and for the "semi-arid" order 8 Powder River watershed (Table 2). At the small scale, the coefficient of determinations ranged from 0.96 to 1.00 for the Horton ratios derived from field data (with one exception, W1165-length, r^2= 0.86). The Horton ratios for slope, bed roughness, and width-to-depth ratio at both large and small scales were nearly equal to 1.

4.2 Hillslope Drainage Network

The number, length, and width of rills (order 0 streams) were measured but the actual drainage area for each rill was not (Table 1). Many order 1 streams began where more than two rills joined. An average of 6.3 rills produced an order 1 stream in W960 and 3.6 rills produced an order 1 stream in W1165. The average rill spacing (total rills/(2 x total stream length)) along all stream orders was 11.5 m in W960 and 10.6 m in W1165.

5.0 Discussion

5.1 Channel Network

Horton ratios computed from the large- and small-scale data were definitely scale invariant and thus, scaled geometrically with stream order. The Horton ratios derived for the small-scale measurements are generally less than those derived from the large scale 30-m DEM. This is expected as the ratios tend to approach an asymptotic value as the scale of the watershed increases (Peckham, 1995). Slopes, bed roughnesses, and width-to-depth ratios are scale invariant in the gullies, but rather than scaling geometrically, these variables are approximately constant (i.e. varying slowly) across all scales. Based on the similarity of the Horton ratios of the topologic variables from both large and small scales, we hypothesize that these hydraulic variables may be scale invariant over larger scales provided larger watersheds are still within similar geological terrain.

5.2 Hillslope Drainage Network

Rills appear to be ephemeral on a decadal time scale in the Spring Creek watershed (Pine, 2002) and were observed to have two different spatial patterns within each watershed. One pattern was nearly parallel rills with a long and narrow drainage shape on small-scale segments of hillslopes that approximate a planar surface with a constant hillslope inclination. The other pattern was a group of rills that converge together to form an order l channel head at the lower end of the obovate-shaped critical drainage area. If this hillslope surface is divided into triangular segments equal to the number of converging rills (6.3 rills in W960 and 3.6 rills in W1165), then each rill can be approximated to flow on a small planar surface.

Planar surfaces appear to be fundamental units composing hillslopes and will by definition have a constant slope. On planar surfaces, flow in rills is straight and parallel. We propose (based on field measurements that indicate nearly constant cross-sectional area with down-slope distance; Moody and Martin, 2001b, Fig. 4.7) that discharge does not accumulate significantly in rills in the downstream direction. This is in contrast to channels networks where discharge can increase abruptly at channel confluences. Sun et al. (1994b) explicitly differentiated hillslopes from channels by assuming hillslopes were those areas with constant slope and with a drainage area less than the critical area for channel initiation (Montgomery and Dietrich, 1994).

Sun et al. (1994b) have shown that the number of order 1 and 2 streams is dependent on inclusion of hillslope processes in theoretical, optimal channel networks. A *hillslope effect ratio* can be defined to be equal to the number of streams in the watershed without hillslope processes divided by the number of streams in the watershed with hillslope processes. The theoretical ratios derived from Sun et al. (1994b, Figure 6) for a watersheds with a hillslope inclination of 30^o were 1.8, 1.1, and 1.0 for order 1, 2, and 3 streams. A similar ratio can be calculated from field data presented in this paper to verify this prediction. The ratio is the number of streams predicted by using the Horton ratio (derived from the large-scale 30-m DEM) divided by the measured number of streams. The *hillslope effect ratios* for W960 are then 1.4, 1.0, and 1.0, values which are very similar to the theoretical *hillslope effect ratio*. For W1165 the *hillslope effect ratios* (4.2, 3.6, and 2.0) are larger suggesting that hillslopes in this subwatershed may have a more dominant role in determining channel networks. These order 1, 2, and some order 3 channels are gullies (width-to-depth ratio <10), which have developed after the wildfire disturbance, as incised features in an interface region between the hillslope and channel network. They are transient and with time will refill with colluvium and revert back to drainages (swales or hollows) on a millennium time scale (Welter, 1995; Moody and Martin, 2001a).

The pattern of the gully and channel network is dependent on the threshold criteria used to define a hillslope. Tucker and Bras (1998) have created channel networks using several hillslope criteria and found differing slope-area and slope-drainage density relations. The simple definition of a hillslope used by Sun et al. (1994b) results in numerous long, parallel channels beginning wherever the area exceeds the critical area on a constant slope. This is not observed in the field and this definition does not account for the concave, obovate surfaces at the head of order 1 channels. Therefore, additional parameters are needed to define the hillslope such as slope or curvature. Slope and critical area have been proposed by Montgomery and Dietrich (1994) and the nature of the concave, obovate surfaces suggests that curvature should be included in the definition of a hillslope.

6.0 Conclusion

The scale invariant property of Horton ratios of topologic variables derived from large scale DEMs (1-1000 km^2) can be used to approximate and simplify channel (width-to-depth > 10) networks at small scales (0.01-1km^2) for modeling purposes. Large-scale DEMs probably do not resolve gullies (width-to-depth < 10) and rills, which are part of the hillslope drainage network. Channel slope, bed roughness, and channel width-to-depth variables have Horton ratios near 1 and thus are constant across scale. Horton ratios of hydraulic variables derived from field measurements at the small scale also are scale invariant and may be extrapolated to the larger scale provided higher order watersheds are within the same geological terrain.

Evidence in this paper supports the theoretical prediction that the watershed drainage network depends on the interaction between hillslope and channel processes in an interface region. The number of gullies (low order streams) in the interface region, required to efficiently drain water from the watershed, were less than the number of channels predicted by using the Horton ratios for the large scale composite 30-m DEM, which did not include hillslope processes. Three regions with differing drainage network characteristics have been identified after erosion following a wildfire: 1) a hillslope region characterized by rills with a decadal time scale, a width-to-depth ratio less than 10, and two spatial patterns; 2) an interface region characterized by gullies with a millennial time scale and a width-to-depth ratio less than 10; and 3) a channel region with a geological time scale and a width-to-depth ratio greater than 10.

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