THESIS

POST-FIRE CHANNEL CHANGE IN TWO SMALL WATERSHEDS IN THE COLORADO FRONT RANGE

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DUNCAN T. ECCLESTON ENTITLED POST-FIRE CHANNEL CHANGE IN TWO SMALL WATERSHEDS IN THE COLORADO FRONT RANGE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT

POST-FIRE CHANNEL CHANGE IN TWO SMALL WATERSHEDS IN THE COLORADO FRONT RANGE

Increased runoff after high-severity wildfire greatly accelerates erosion and incises rills and gullies into previously unchanneled hillslope swales. Elevated peak flows transport this sediment through ephemeral and perennial channels, and these may either erode or aggrade. Low-order drainages are of critical interest to downstream water managers because they are the primary sources of water and sediment, yet post-fire channel change is poorly understood. The objectives of this study were to: (1) compare channel head locations and channel morphology between burned and unburned watersheds; (2) determine whether slope and contributing area can predict the transition from incising to aggrading drainages; (3) measure cross-sectional changes over time in different drainage types (rills, gullies, ephemeral channels, and perennial channels); (4) determine how drainage type, precipitation, watershed- and reach-scale variables affect cross-sectional channel change; and (5) use particle size data to enhance the understanding of the study watersheds' response to the Hayman fire as well as previous fires.

Geomorphic data were collected from two small (3.4 and 6.0 km^2) watersheds in the Colorado Front Range that burned in summer 2002 and two similar 4.6 and 5.5 km^2 unburned watersheds. In the burned watersheds, 72 cross-sections were established in 6 gullies, 9 ephemeral and 6 perennial channel reaches in May 2004. These were re-surveyed 2–5 times following major storms in summer 2004, after snowmelt in May

2005, and at the end of the study in November 2005. Rill data from other studies also were analyzed.

Contributing areas above the channel heads in the burned watersheds were approximately three orders of magnitude smaller than in the unburned watersheds. Unstable banks and knickpoints were far more prevalent in the burned watersheds, and channel widths were greater. When stratified by flow regime, fine bed material was more prevalent in the burned watersheds. The transition from incising gully to aggrading channel could not be accurately predicted using slope or area. In summer 2004 rainfall intensities greater than 14 mm hr^{-1} generally caused watershed-wide floods, and the magnitude of cross-sectional change was inversely proportional to antecedent moisture. These floods caused the rills and gullies to incise and channels to aggrade. From October 2004 to November 2005 reach change was primarily due to snowmelt runoff and colluvial processes. Because post-fire runoff rates have declined, the rills and gullies are expected to slowly fill with colluvium, the ephemeral channels will store the post-fire sediment until the next wildfire, and the sediment currently stored in the perennial channels will slowly be evacuated. The results suggest that drainage scale and flow regime are important controls on the direction, magnitude, and persistence of post-fire changes, and that the watershed response to multiple wildfires is an important control on long-term valley morphology and flow regime.

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1. INTRODUCTION

Most erosion in the Colorado Front Range is hypothesized to occur after fires (Morris and Moses, 1987). In the Western United States wildfires and the subsequent floods are the primary catalysts for episodic sediment delivery to streams (Swanson, 1981; Miller et al., 2003; Istanbulluoglu et al., 2004). Because erosion rates on a millennial time scale are strongly influenced by short periods of rapid erosion (Kirchner et al., 2001), landforms in arid and semi-arid landscapes may be formed primarily by large, infrequent events, such as wildfire and floods (Brunsden and Thornes, 1979).

Low-order channels are the critical sediment pathways from burned areas to larger rivers and reservoirs that provide fish habitat and the public water supply. Therefore, incision or aggradation high in the drainage network is of critical interest to land and water managers concerned about elevated sediment loads downstream. Although post-fire hillslope erosion rates generally decline to near-background levels within five years after burning (Moody, 2001; Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006), channel adjustments due to to the changes in runoff and sediment supply may continue for much longer (Benda et al., 2003). Sediment yields at the watershed scale can remain elevated long after the hillslope recovers (Helvey, 1980) because temporarily stored sediment continues to be mobilized (Walling, 1983). Large watersheds have more low stream power storage locations that slow sediment delivery, so relaxation time in perennial watersheds may be proportional to contributing area (Wells, 1981).

The magnitude, duration, and timing of post-fire incision and aggradation in low-order channels is influenced by the spatial scale (Moody and Martin, 2001b), presence of perennial flow (Laird and Harvey, 1986), and annual hydrograph (Reneau et al., 2007). Post-fire sediment deposits may be evacuated (Legleiter et al., 2003), depending on the magnitude, duration (Kasai et al., 2004), and spatial extent (Meade, 1982) of geomorphically effective flows. However, post-fire sediment can be stored in ephemeral or intermittent channels for decades or longer (Laird and Harvey, 1986; Wohl and Pearthree, 1991), or in floodplains, terraces or alluvial fans for centuries or millennia (Meyer et al., 1995; Moody and Martin, 2001b).

1.1. EFFECTS OF BURNING ON RUNOFF AND HILLSLOPE EROSION

Hillslope-scale effects of high and moderate severity fires include loss of vegetative cover, reduced evapotranspiration (Ice et al., 2004), and reduced infiltration due to the establishment of a water-repellent layer at or near the soil surface (DeBano, 2000; Letey, 2001) and/or soil sealing (Neary et al., 1999). These changes mean that rainfall intensities of 8–10 mm hr^{-1} are sufficient to initiate overland flow on the hillslope in the first two to three years after a high-severity fire in the Colorado Front Range (Moody and Martin, 2001b; Pietraszek, 2006). In the first two years after burning peak flows can be 60–100 times greater than the flows from similar storms in subsequent years (Moody and Martin, 2001c).

In the Colorado Front Range, hillslope erosion rates after a high-severity wildfire can increase by two or more orders of magnitude (Morris and Moses, 1987; Robichaud et al., 2000; Benavides-Solorio and MacDonald, 2001). Summer convective storms generate at least 90% of post-fire sediment yields at the hillslope scale (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). During these storms, increased runoff and the absence of vegetation accelerate rainsplash and sheetwash erosion on planar hillslopes

(Doehring, 1968; Florsheim et al., 1991, Morris and Moses, 1987; Wondzell and King, 2003; Pietraszek, 2006). Sheetwash is concentrated by micro-topography on planar hillslopes and in hillslope swales that were unchannelized before burning (Moody and Martin, 2001b; Libohova, 2004). Concentrated flow induces rilling, which extends the drainage network onto the hillslope and further increases erosion (Moody and Martin, 2001b). Planar hillslopes with rills produce sediment at two or more times the rate as hillslopes without rills (Pietraszek, 2006), and convergent hillslopes produce more than twice as much sediment as planar hillslopes (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006).

Post-fire runoff and sediment production rates decline as vegetative cover increases (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006), the water-repellent layer breaks down (MacDonald and Huffman, 2004), and the soil surface becomes armored (Morris and Moses, 1987). Vegetative cover generally exceeds 50% by the third or fourth summer after high-severity fires in the Colorado Front Range (Pietraszek, 2006). Post-fire soil water repellency attenuates within one year in the Colorado Front Range (MacDonald and Huffman, 2004) to a maximum of six years in Northern Arizona (Dyrness, 1976, in Wondzell and King, 2003). A coarse armored layer develops at the soil surface within three years of burning (Morris and Moses, 1987; Thomas et al., 1999; Moody and Martin, 2001b), and this reduces rainsplash and hydraulic erosion. The majority of post-fire erosion occurs in the first three years after a high-severity fire, and the relaxation time, or period required for hillslope sediment yields to decline to pre-fire levels, is typically five years or less (Moody, 2001; Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006).

1.2. INITIAL RESPONSE TO WILDFIRE IN THE DRAINAGE NETWORK

Elevated peak flows and erosion propagate downstream through the drainage network after high-severity wildfires (Simon 1999; Miller et al., 2003). The headwater rills generally become wider and deeper as the contributing area increases. Multiple rills form gullies, which are morphologically similar to rills but too large to be removed by plowing. In this study, gullies were defined as reaches that have incised since the fire (>90% by length) and are at least 0.5 m wide and 0.2 m deep. They are generally have contributing areas less than 5 ha, channel slopes greater than 12%, and width-to-depth ratios that are less than 10. Rill and gully erosion accounts for 70–80% of the post-fire sediment yields from very small (0.2–7 ha) watersheds in the Colorado Front Range (Moody and Martin, 2001b; Pietraszek, 2006).

A high rate of sediment production at the hillslope scale causes downstream deposition (Schumm, 1977). Numerous studies have documented the high erosion rates after fires from hillslopes, rills, and gullies, and the subsequent deposition in transport-limited channels downstream (Helvey, 1980; Laird and Harvey, 1986; Florsheim, et al. 1991; Minshall et al., 1998; Moody and Martin, 2001b). For this study, channels are functionally defined as the ephemeral or perennial portions of the drainage network that are downstream of gullies and have aggradation as the dominant post-fire process. The terms gully and channel succinctly differentiate between the zones of initial post-fire incision and aggradation, respectively.

Unit stream power can be used to determine whether a reach will incise or aggrade (Bull, 1979). Unit stream power, ω, is the energy available to transport the sediment load per unit width of the channel, and this is defined as:

$$\omega = \gamma R S V \qquad (1)$$

where γ is the specific weight of the fluid (N m^{-3}), R is the hydraulic radius approximated by mean depth (m), S is the slope of the energy gradient (dimensionless), and V is the mean velocity (m sec^{-1}) (Bagnold, 1966, in Madej and Ozaki, 1996). Critical unit stream power, ω^*, is the energy threshold necessary to transport the sediment load already in motion, and this varies with sediment supply, grain size, and bed roughness (Bull, 1979). The average ω^* over the sequence of post-fire floods defines the gully-channel transition. In post-fire gullies, ω generally exceeds ω^* and scour occurs. For post-fire channels as defined in this study, ω is generally less than ω^* and aggradation initially predominates.

The magnitude and regime of water flows and sediment loads are key controls on channel morphology (Bull, 1979). Channels respond to changes in runoff and sediment supply by adjusting width, depth, slope, velocity, bed roughness, and plan-form geometry (Phillips, 1991). A single stream generally displays multiple adjustments, which can vary spatially and temporally (Phillips, 1991). After a wildfire, the increase in sediment supply is generally larger than the increase in flows downstream of the gully-channel transition. Therefore, wildfires generally cause aggradation, widening, braiding, increased width-to-depth ratio, and decreased sinuosity in the channels (Doehring, 1968; Laird and Harvey, 1986; Florsheim et al., 1991; Minshall et al., 1998; Moody and Martin, 2001b). Unstable banks and knickpoints are common features in some post-fire channels (Laird and Harvey, 1986; Libohova, 2004) and indicate rapid geomorphic adjustment.

The channel response to high-severity wildfires can be site specific. Localized incision can occur in confined or steep reaches, or where knickpoints retreat upstream (Doehring, 1968; Moody and Martin, 2001b). Contributing area (Minshall et al., 1998), valley width (Florsheim et al., 1991), slope (Doehring, 1968), and flow regime (Laird and Harvey, 1986) all can be locally important controls on reach response. Zelt and Wohl (2004, p. 218) state that the current understanding of channel response to wildfire “is limited by the multitude of affected processes and controls, and by dependence on local site characteristics.”

The initial response to high-severity wildfire, called Phase I in this study, is characterized by storm-driven erosion high in the drainage network that causes rapid aggradation in lower gradient reaches immediately downstream. Sediment evacuation from small watersheds is episodic during Phase I; in the Colorado Front Range summer stormflows remove approximately twice as much sediment from a small watershed as snowmelt runoff and baseflows combined (Moody and Martin, 2001b).

Phase I is short-lived because the rainfall-runoff response and hillslope-scale sediment production quickly approach pre-fire conditions (Moody and Martin, 2001b), which reduces peak flows and sediment delivery to downstream channels. In ephemeral channels with alluvial beds, surface flow and sediment transport can become very rare if the alluvium is deep enough to transmit stormflows subsurface (Laird and Harvey, 1986).

1.3. LONG-TERM POST-FIRE CHANGES TO THE DRAINAGE NETWORK

Phase II is the recovery period following Phase I, when drainage network change is driven primarily by colluvial processes, snowmelt runoff, and baseflows because runoff and hillslope erosion rates have returned to near pre-fire levels. Hence Phase II begins when summer storms no longer cause runoff at the hillslope scale and floods at the watershed scale. Once large volumes of sediment are no longer washed into the channels by most storms, recovery begins (Florsheim et al., 1991; Keller at al., 1997). The rills and gullies slowly refill (Moody and Martin, 2001b), whereas the low-order perennial channels typically evacuate sediment and incise (Keller et al., 1997). Phase II ends when the rate of sediment evacuation from the perennial channels returns to background levels, whereupon the drainage network enters the undisturbed, Phase III state.

In the Rocky Mountains, sediment evacuation from perennial channels is driven primarily by snowmelt runoff (Legleiter et al., 2003; Reneau et al., 2007), and to a lesser extent by baseflows and stormflows (Reneau et al., 2007) because of the decline in the rainfall-runoff response. The magnitude of snowmelt runoff volumes and peak flows can be increased by wildfires due to increased solar radiation (Helvey, 1980), increased turbulent heat transfer (Baker, 1986), and decreased albedo due to ash deposition from standing burned trees (Helvey, 1973 in Tiedemann et al., 1979). These effects are magnified by concurrent changes in the water balance due to: (1) a larger snowpack caused by reduced canopy interception; and (2) decreased available soil moisture storage capacity as a result of reduced evapotranspiration (Troendle and King, 1985). After the Yellowstone fires, the duration of medium-high and high flows during spring snowmelt increased in a burned watershed relative to an unburned control, and annual water yields were approximately 30% higher (Troendle and Bevenger, 1996). Elevated post-fire snowmelt flows may be most marked in humid environments where evapotranspiration is a larger component of the water balance (Robichaud et al, 2000). Elevated snowmelt runoff may persist for several decades while interception and evapotranspiration rates slowly increase due to canopy regrowth (Troendle and King, 1985; Robichaud et al., 2000).

Snowmelt generally infiltrates and travels by subsurface pathways to the channels, so colluvial processes, such dry ravel and as bank collapse due to winter freeze-thaw, are the primary cause of aggradation in the rills and gullies (Moody and Martin, 2001b; Pietraszek, 2006). This material generally is not transported to the channels downstream because snowmelt does not cause surface flow in the rills or gullies (Pietraszek, 2006).

Because little additional sediment is supplied to the perennial channels during Phase II, the sediment deposited in Phase I is slowly evacuated from the perennial channels. Elevated snowmelt flows incise low flow channels into the post-fire deposits, and may eventually evacuate the post-fire sediment from perennial channels (Legleiter et al., 2003). Ten years after the Yellowstone wildfires, first-order channels in burned watersheds that initially aggraded were not morphologically different from those in unburned watersheds (Ernstrom, 1999). Within thirteen years of the Yellowstone fires, second- to fourth-order channels that initially aggraded had become incised relative to the channels in unburned watersheds (Legleiter et al., 2003).

After a sediment pulse, the bed surface typically coarsens once the sediment supply returns to background levels if streamflows are unchanged or increase (Lisle et al., 2000). The particle-size distribution of bed material is often a key monitoring parameter (Montgomery and MacDonald, 2002), and an increase in median particle size can indicate channel recovery after disturbance (Dietrich et al., 1989). Within thirteen years of the Yellowstone fires, the bed in the second- to fourth-order channels had become armored and the streams had returned to their pre-fire, supply-limited state (Legleiter et al., 2003). Once the bed becomes armored, the rate of incision slows considerably (Moody and Martin, 2001b).

1.4. PROBLEM STATEMENT AND OBJECTIVES

In June 2002 the Hayman fire burned over 55,000 ha in the Upper South Platte River watershed in the Colorado Front Range, approximately 50 km southwest of Denver (Graham, 2003). Previous studies of the Hayman fire quantified post-fire hillslope and rill erosion in response to summer storms (e.g., Pietraszek, 2006; Rough, 2007) and noted major aggradation in the ephemeral and perennial channels further downstream (Libohova, 2004).

The goal of this study was to improve the understanding of post-fire morphological changes in low-order drainages with respect to spatial scale (rills and gullies vs. downstream channels), flow regime (ephemeral vs. perennial), and seasonal response (summer thunderstorm vs. snowmelt). The specific objectives were to: (1) compare channel head locations and channel morphology between burned and unburned watersheds; (2) determine whether slope and contributing area can predict the transition from incising to aggrading drainages; (3) measure cross-sectional changes over time in different drainage types (rills, gullies, ephemeral channels, and perennial channels); (4) determine how drainage type, precipitation, watershed- and reach-scale variables affect cross-sectional channel change; and (5) use particle size data to enhance the understanding of the study watersheds' response to the Hayman fire as well as previous fires.

An understanding of the topographic determinants of post-fire channel heads and gully-channel transitions could help predict where drainage networks will incise or aggrade. This analysis could help plan site specific treatment applications when few field data are available and therefore maximize the effectiveness of rehabilitation treatments. Cross-sectional data can be used to estimate rates of sediment flux, and therefore recovery rates, for the different drainage types. These recovery rates can be used to help predict the persistence of post-fire sediment deposits, as well as the long-term influence of wildfires on valley morphology in the Colorado Front Range. Finally, documentation of the intra- and inter-reach variability in post-fire channels may help maximize the efficiency of other data collection efforts in disturbed environments.

2. SITE DESCRIPTION

The study was conducted in the Pike-San Isabel National Forest, in the northeast corner of the area burned by the Hayman fire (Figure 1). Field measurements focused on two small, mountainous burned watersheds and two similar unburned watersheds that enter the Upper South Platte River near Trumbull, Colorado at an elevation of approximately 1950 m (Figure 1). Forty-eight percent of the 3.4 km^2 Saloon Gulch watershed burned at high severity, 5% at moderate severity, and 47% percent at low severity in the Hayman fire or was unburned (USFS, unpublished data). Sixty-three percent of the 6.0 km^2 Brush Creek watershed burned at high severity, 3% at moderate severity, and 34% at low severity or was unburned (USFS, unpublished data). In both Saloon Gulch and Brush Creek, most of the high-severity burn occurred in the upper watershed. The two unburned watersheds, Jenny Gulch and Scraggy View Gulch, were selected because they are similar to Saloon Gulch and Brush Creek with respect to contributing area, vertical relief, main channel length, and main channel slope (Table 1).

Variable	Burned		Unburned	
	Saloon Gulch	Brush Creek	Scraggy View Gulch	Jenny Gulch
Contributing area (km^2)	3.4	6.0	5.5	4.6
Vertical relief (m)	630	670	730	540
Aspect	E	SE	SE	W
Percent burned at high or moderate severity	53	66	0	0
Main channel length (km)	4.0	5.1	4.1	4.5
Main channel slope (%)	11	9	9	9
Main valley width (m)	30.7	13.2	8.2	8.8
Predominant flow regime	Ephemeral	Perennial	Ephemeral	Perennial

Table 1. Key characteristics of the two watersheds that were partially burned by the Hayman wildfire and the two nearby unburned watersheds.

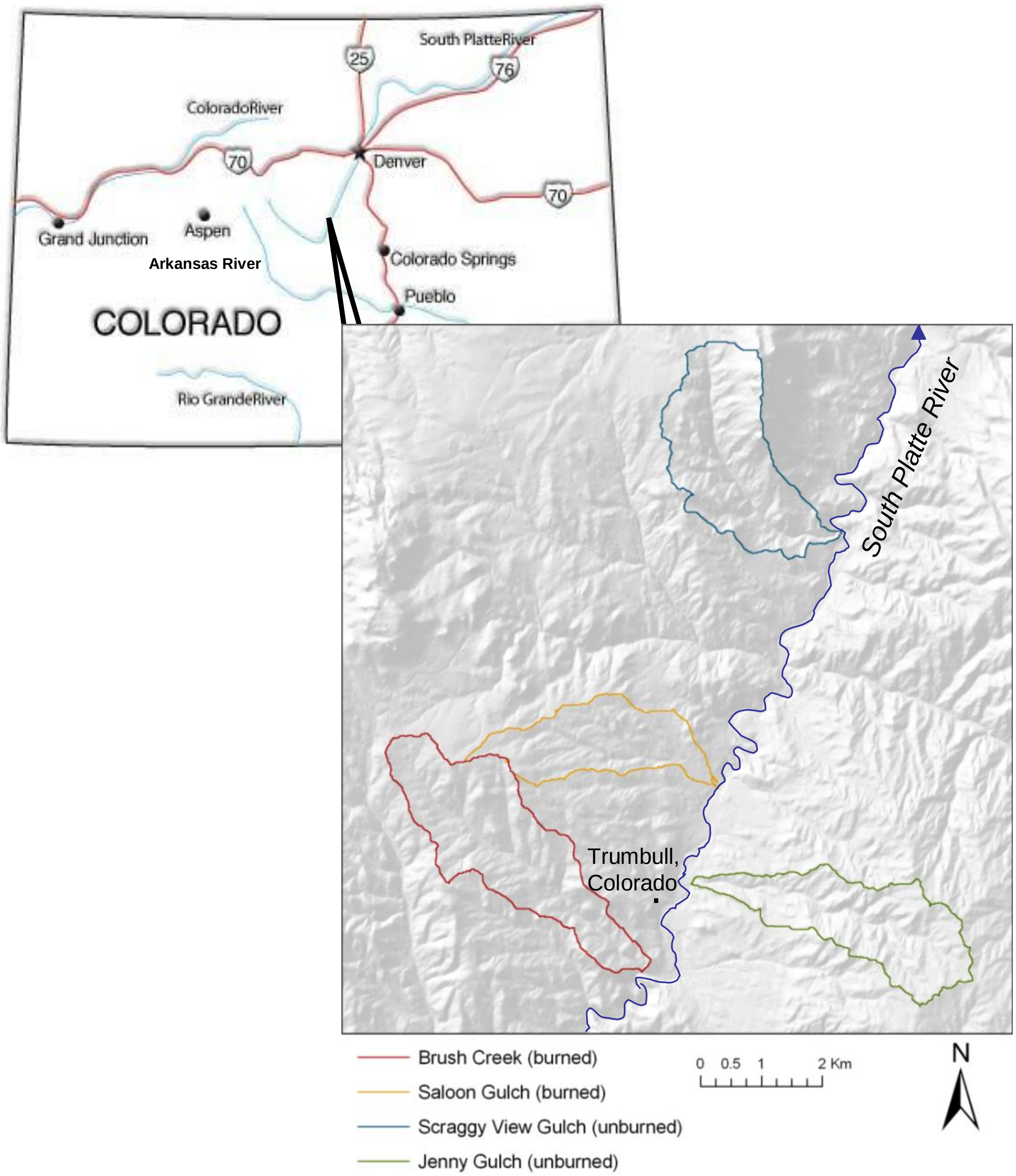


Figure 1. Map of the four study watersheds. About 55% of the Saloon Gulch watershed and 65% of the Brush Creek watershed burned at high or moderate severity in the 2002 Hayman fire, whereas Scraggy View Gulch and Jenny Gulch were unburned.

Prior to burning, ponderosa pine (*Pinus ponderosa*) forest was the dominant vegetation type (Pietraszek, 2006). The highly erodible soils in the study area are coarse gravelly sandy loams formed from the granite of the Pikes Peak batholith (Moore, 1992). Under unburned conditions the permeability of the dominant Sphinx soil series is 15–51 cm hr^{-1} (Moore, 1992). Mean annual precipitation is 410 mm, and approximately 35% falls as snow (NOAA, 2006). The balance falls as rain during frontal storms in April and May, or in short, intense thunderstorms during June–September. The one-year, 30-minute storm is estimated by the WEPP CLIGEN computer model to be 10 mm, with an associated rainfall intensity of 20 mm hr^{-1} (D. Hall, USDA Forest Service Rocky Mountain Research Station, pers. comm., 2004); Hershfield (1961) estimated the one-year, 30-minute storm to be 11.5 mm, with an associated rainfall intensity of 23 mm hr^{-1}.

In summer 2001 11 pairs of hillslope scale plots were established in Saloon Gulch to assess the potential effects of a forest thinning project (Libohova, 2004). Before the Hayman fire, there was 88% ground cover and the hillslope plots produced no sediment (Libohova, 2004). The Hayman fire reduced ground cover to 6%, and the hillslope plots produced sediment at a rate of 0.67 kg m^{-2} during one 11.2 mm storm in 2002 (Libohova, 2004). By summer 2004 the mean percent bare soil on the severely-burned hillslopes had dropped to 55%, and the rate of sediment production had declined (Pietraszek, 2006; Rough, 2007). In a different study, various post-fire rehabilitation treatments were applied to test plots in Saloon Gulch and Brush Creek in 2002, but the treated area comprised less than 1% of the watershed, and by summer 2004 only two of the four had any significant effect on hillslope-scale sediment yields (Rough, 2007).

The Saloon Gulch watershed has 630 m of vertical relief and an easterly aspect (Table 1). Defined as the highest order channel from the bottom of the watershed to the top, the main channel in Saloon Gulch is 4.0 km long with a mean slope of 11% (Table 1). The main channel has perennial flow in some upper reaches where the valley is confined or bedrock is exposed. A steep bedrock band divides Upper and Lower Saloon Gulch (Figure 2).

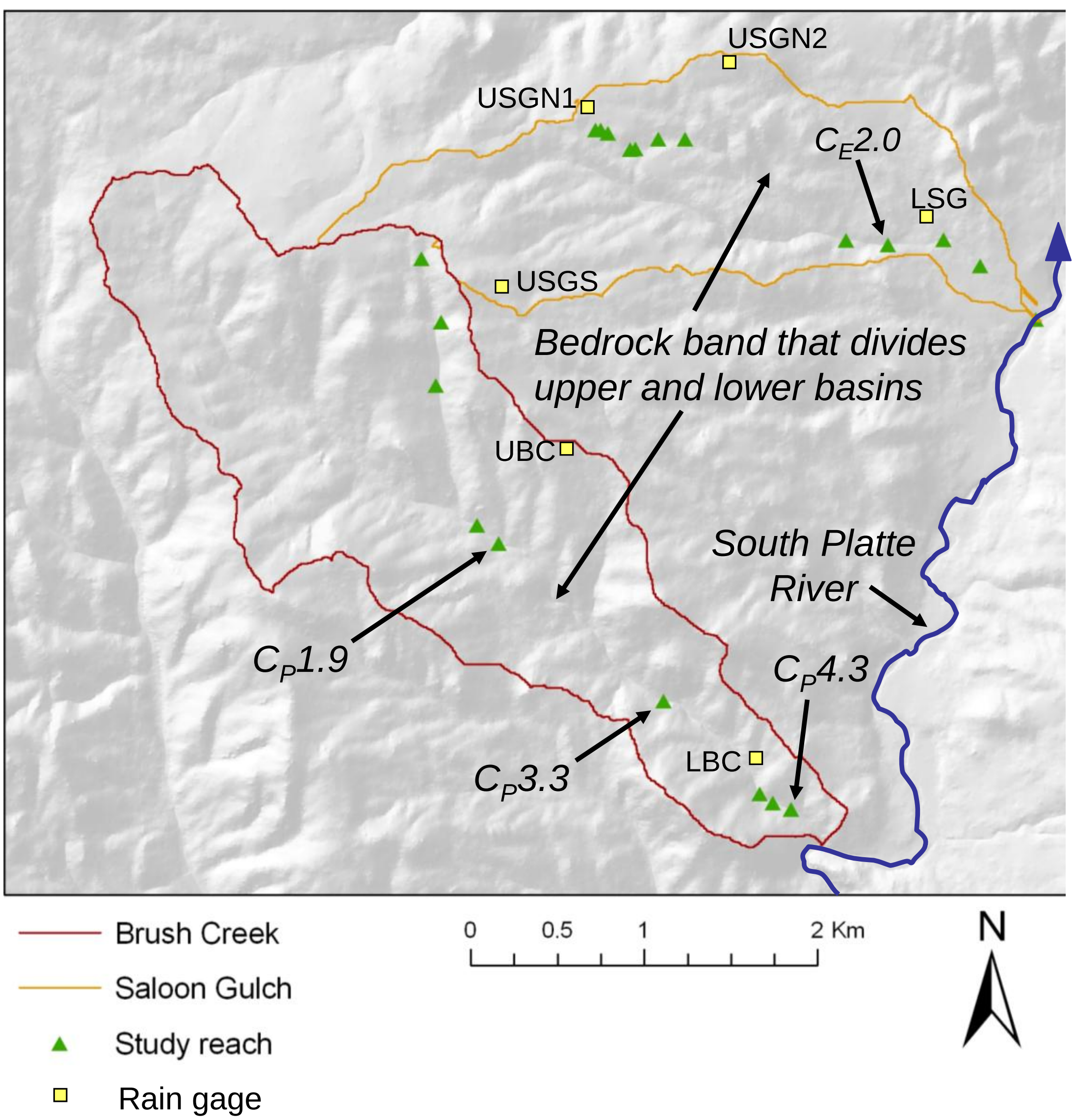


Figure 2. Map of rain gages, study reaches, key cross-sections discussed in the results, and other landscape features in the two burned watersheds.

After the fire, rilling was initiated on most planar hillslopes and where flow is concentrated by convergent topography (Figure 3). Rills become wider and deeper moving downstream, and generally become gullies where the contributing area is about 0.5–1 ha (Figure 4). The gullies drain into flatter aggrading ephemeral channels. In Upper Saloon Gulch these channels are typically 2–8 m wide with low, eroding banks that suggest recent widening (Figure 5). The bed surface is generally planar in cross-section and longitudinally. In the upper watershed the ephemeral channels are confined by steep valley walls.

Figure 3. Rills developed in the swale axes as a result of the first rainstorms after the Hayman Fire.

Figure 4. Deep gully in Brush Creek in summer 2004. The slope is about 17% and the contributing area is about 10 ha.

Figure 5. A moderately confined ephemeral channel reach in Upper Saloon Gulch in summer 2004. The slope is about 9% and the contributing area is about 0.25 km^2.

In Lower Saloon Gulch the width of the main valley ranges from 20–103 m with an average of 66 m. The channel itself is nearly planar, in both cross-section and longitudinally, and it has a slope of 8–10%. Before the fire, perennial flow extended about one kilometer downstream of the bedrock band, but extensive post-fire aggradation buried the pre-fire channel (Libohova, 2004; L. MacDonald, Colorado State University, pers. comm., 2004). The valley topography indicates that the alluvium in the main valley is tens of meters deep in the lower sections. The aggradation and deep alluvium meant that there was no perennial flow in Lower Saloon Gulch at the beginning of this study in May 2004. Much of the channel is braided, and these are the only bedforms, aside from eight knickpoints 0.2–0.7 m high. At the confluence of Saloon Gulch and the South Platte River there is an additional knickpoint that was 1–2 m high before the fire (R. Johnson, Swayback Ranch Fishing Club, pers. comm., 2004), and this represents the truncation of the alluvial fan coming from Saloon Gulch.

The Brush Creek watershed has 670 m of vertical relief and a southeasterly aspect (Table 1). The main channel is 5.1 km long with a mean slope of 9%, and is predominantly perennial (Table 1). The rills, gullies, and ephemeral channels of Upper Brush Creek are very similar to those in Upper Saloon Gulch. However, perennial flow begins approximately one kilometer upstream of the bedrock band that divides Upper and Lower Brush Creek, and this continues to the South Platte River. The main channel in Lower Brush Creek is highly confined by a V-shaped valley that averages 10 m across (Figure 6; Figure 7). The channel slope ranges from 4% to as much as 30% in two short bedrock sections. Sediment storage occurs in a few discontinuous terraces where the valley is comparatively wide and the channel slope is low (Figure 7). Banks are composed primarily of unconsolidated fine-textured pre-fire alluvium, anchored by roots with some gravel and cobbles. Since the fire, both bank erosion and incision have occurred along the confined channel. There is not a large alluvial fan or knickpoint at the confluence of Brush Creek with the South Platte River.

Figure 6. Typical confined perennial channel reach in Lower Brush Creek in summer 2004. The slope is about 6% and the contributing area is about 5.9 km^2.

The mean contributing area, vertical relief, main channel length, and slope for unburned watersheds were all within 10% of the means for the burned watersheds (Table 1). The main valley in Saloon Gulch was 30.7 m across, or about three times wider than the average among the other watersheds (Table 1). Scraggy View Gulch and Saloon

Gulch are predominantly ephemeral (Table 1), and a truncated alluvial fan at the outlet of each watershed with a 1–2 m knickpoint indicates extensive prior aggradation. In contrast, Jenny Gulch and Brush Creek are predominantly perennial (Table 1), and there is no knickpoint or other evidence of extensive aggradation at the outlet of either watershed.

Figure 7. Study reach C_P3.3 in summer 2004. This is one of several reaches in Lower Brush Creek with extensive post-fire aggradation.

3. METHODS

3.1. DRAINAGE NETWORK CHARACTERISTICS

The channel heads were identified and characterized in each of the four watersheds. In summer 2005, 14 channel heads were identified in burned watersheds by randomly selecting gullies draining into the study reaches in severely-burned areas, and following these upstream until the banks were no longer distinct (Dietrich and Dunne, 1993). In each of the unburned watersheds there were only two channel heads. The slope above and below each channel head was measured with a clinometer, and the location was recorded with a handheld, differentially corrected global positioning system (GPS) unit.

Thirty-two gully-channel transitions were identified in September 2004 in the burned watersheds by following each channel upstream until the upstream drainage became predominantly (>90% by length) incised. Channel slope above and below the gully-channel transition was measured over a distance of approximately 10 m with a clinometer, and the location of the transitions were recorded using a GPS unit. All 32 gully-channel transitions were re-visited in June 2005, and 10 sites were re-visited in November 2005 to determine whether these transitions had migrated over time.

A channel inventory was conducted in June–July 2005 for all of the channels in the burned watersheds, and in September–October 2005 for the main channels in the unburned watersheds. Reaches were defined as having consistent groups of bedforms that were at least 10 channel widths long (Montgomery and Buffington, 1997). There were 22 to 33 reaches in each watershed.

For each reach the valley width, active width, thalweg depth, bed material, bank vegetation, bank condition, presence of surface flow, number of channels, and number of knickpoints were measured, classified, or counted as described in Table 2. The confinement ratio, defined as the active width divided by the valley width, and the width-to-depth ratio were calculated from the field measurements. The upstream and downstream boundaries of each reach were recorded with a GPS unit.

Variable	Definition	Measurement
Valley width	The lateral distance between the valley walls confining the active channel.	Average of 3 or more measurements.
Active width	The lateral distance between the outermost signs of post-fire scour or deposition. Bankfull width in unburned watersheds. The sum of all active widths in multiple thread channels.	Average of 3 or more measurements.
Thalweg depth	The vertical distance from the thalweg to bankfull, or from the thalweg to the highest recent deposit or scour if that distance was greater. Bankfull depth in unburned watersheds.	Average of 3 or more measurements.
Confinement	The mean active width divided by the mean valley width.	Calculated from reach measurements
Width-to depth ratio	The mean active width divided by the mean depth.	Calculated from reach measurements
Bed material	The material within the active channel compared to the bed material in the ephemeral channels in the burned watersheds, with D_{50} ~4 mm	Visual classification: (1) similar; (2) coarser; or (3) bedrock.
Bank vegetation	Percent cover in the first meter outside of the active channel .	Visual classification: (1) <25%; (2) 25-50%; or (3) >50%.
Bank condition	An assessment of the stability of the vertical portions of the active channel and its boundaries	Visual classification as: (1) stable and uncut; (2) cut into hillslopes or pre-Hayman material; (3) cut into post-Hayman deposits; or (4) cut into both pre-Hayman material and post-Hayman deposits.
Surface flow	The presence or absence of surface flow at least one month after a large storm.	Visual classification: (1) yes; or (2) no.
Number of channels	The number of active channels separated by inactive areas.	Visual classification: (1) single; or (2) multiple.
Knickpoints	Unstable cuts at least 20 cm deep.	Count.

Table 2. Definitions and measurement techniques for the reach-scale variables assessed in the channel inventory.

All of the GPS points were differentially corrected using Pathfinder Office 2.90 (Trimble, 2003) and imported into ArcGIS 9.0 (ESRI, 2005). Drainage networks with contributing areas of at least 50 m^2 and watersheds were delineated in ArcGIS 9.0 using a 5 m DEM created from high resolution Interferometric Synthetic Aperture Radar (IFSAR) data. The channel heads, gully-channel transitions, and reach boundaries were all in topographically convergent areas, but some GPS points had to be manually corrected in order to overlay the GIS-delineated drainage network.

Contributing area was calculated for each channel head, gully-channel transition, and downstream reach boundary using the DEM and ArcGIS 9.0. For the channel heads, the difference in median contributing area and downstream slope between the burned and unburned watersheds was tested using the non-parametric Wilcoxon rank sum test. Linear regression was used to assess the relationship between contributing area and downstream slope for the channel heads in the burned watersheds. For the gully-channel transitions, downstream slope was plotted against contributing area to determine whether there was a threshold for the location of these transitions, and the difference between upstream and downstream slopes were calculated to determine whether their location was controlled by a consistent difference in channel slope.

Reach lengths were measured by tracing the drainage network with the on-screen measuring tool in ArcGIS 9.0. Channel slope was calculated from the difference in elevation between the reach endpoints divided by channel length. Confinement was calculated by dividing the mean width of the active channel by the valley width (Table 2). Burn severity layers created by the United States Forest Service (USFS, 2002) were used to determine the proportion of unburned area as well as the amount burned at low-, moderate-, and high-severity within the contributing area of the bottom of each reach. Channel slope*depth was calculated for each reach as a surrogate for stream power, because the hydraulic radius, specific weight of the fluid, and flow velocity during floods were unknown.

Channel geometry and the other channel inventory variables were summarized for the main channels in each watershed by calculating length-weighted averages for each continuous variable, and calculating the percent of the total length for each categorical variable. These summary data were used to compare the channel characteristics between the burned and unburned watersheds. For comparing variables that could be influenced by perennial surface flow such as bed material size, Saloon Gulch was paired with Scraggy View Gulch, and Brush Creek was paired with Jenny Gulch (Table 1).

A histogram was constructed to show the number of reaches by contributing area for each watershed (Figure 8). Saloon Gulch had more reaches with very small (<1 km^2) contributing areas and no reaches with a contributing area larger than 3.9 km^2. Brush Creek had more reaches with a contributing area larger than 5 km^2. Both Scraggy View Gulch and Jenny Gulch had a reasonable distribution of reaches from the smallest class (<1 km^2) up to 4.9 km^2. Overall, the only distinct difference between the burned and unburned watersheds was the large number of reaches with small contributing areas in Saloon Gulch and the larger number of reaches with large contributing areas in Brush Creek.

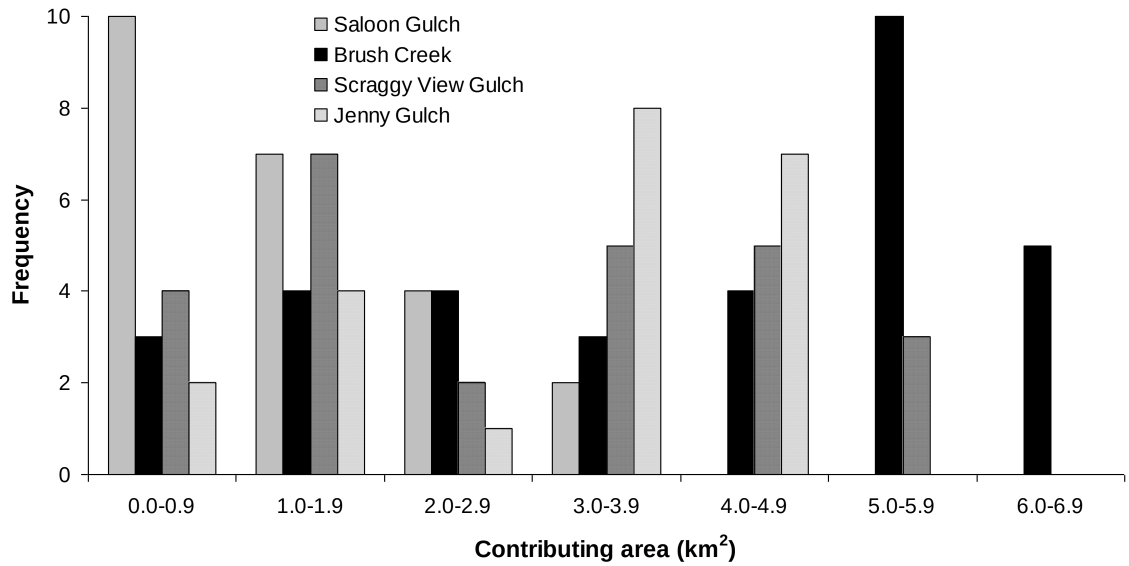


Figure 8. Histogram showing the number of main channel reaches by contributing area for the burned and unburned watersheds.

The mean active width for each reach was plotted against its contributing area to assess the downstream channel geometry for each watershed (Figure 9). The only significant relationship was for Saloon Gulch (R^2=0.69; p <0.0001).

Figure 8 does not show a consistent difference in the contributing area of the study reaches between the burned and unburned watersheds, and Figure 9 indicates that the active width is related to contributing area only for Saloon Gulch. On this basis, the data from each reach were treated as an independent sample. The continuous variables measured in each reach were tested for significant differences between the burned and unburned watersheds using Student's t-test. In conducting these tests, all reaches were weighted equally regardless of reach length.

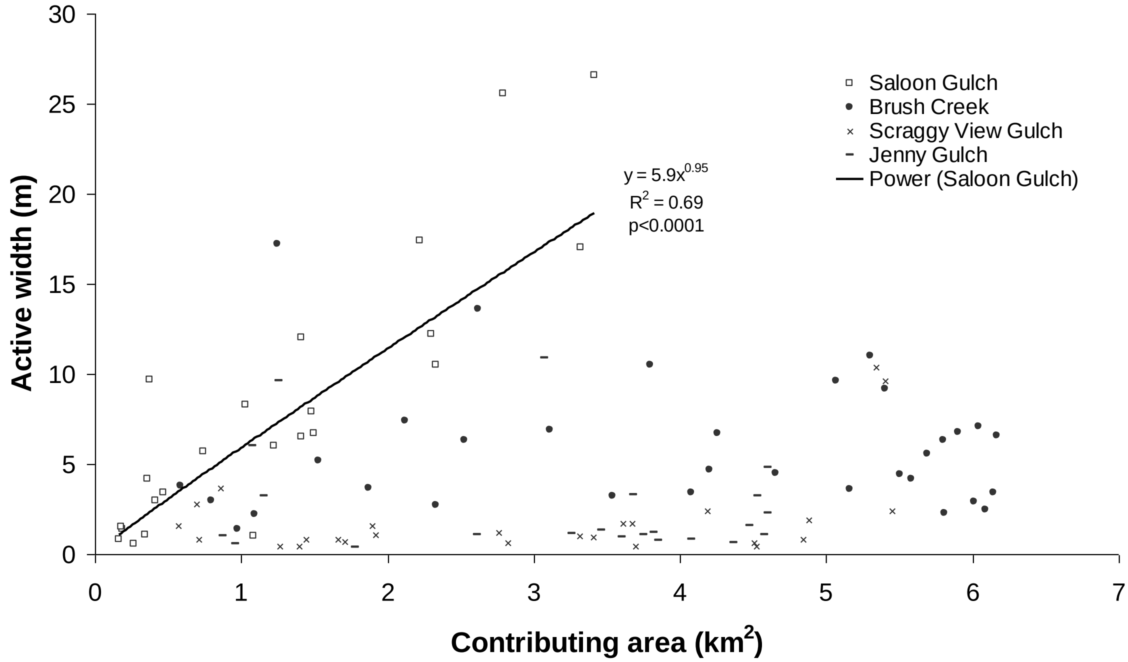


Figure 9. Relationship between contributing area and active width for each of the four watersheds.

3.2. PRECIPITATION, ANTECEDENT MOISTURE, AND STREAMFLOW

Precipitation was measured by six tipping bucket rain gages with either 0.01 in or 0.2 mm resolution. Saloon Gulch had one gage in the lower watershed and three in the upper watershed; Brush Creek had one gage in the lower watershed and one in the upper watershed (Figure 2). The most valid data were collected during the summer monitoring seasons, which were from 21 May to 23 October 2004 and 21 May to 27 November 2005. Tipping bucket data also were collected during the winter, but this was only valid for documenting rainstorms because the tipping bucket gages do not accurately measure snowfall.

The rainfall data were used primarily as a surrogate for streamflow because of the difficulties in measuring runoff as described below. The rain gages used to characterize precipitation within the contributing areas of the study reaches in the upper and lower portions of each burned watershed are listed in Table 3. The Upper Saloon Gulch South (USG South) gage was used to represent rainfall in both watersheds because it was so close to the watershed divide (Figure 2). The four rain gages in Saloon Gulch were well distributed, but some areas in Upper Brush Creek were up to 3 km from the nearest gage.

Watershed	Gages
Upper Saloon Gulch	USGN1, USGN2, USGS
Lower Saloon Gulch	USGN1, USGN2, USGS, LSG
Upper Brush Creek	UBC, USGS
Lower Brush Creek	UBC, USGS, LBC

Table 3. List of the gages used to represent precipitation in the contributing areas of the study reaches in the upper and lower portions of Saloon Gulch and Brush Creek.

A storm was defined as at least 5 mm of precipitation between periods of at least one hour with no rainfall. Storm rainfall (mm), the maximum thirty-minute intensity (I_{30}, mm hr^{-1}), and erosivity (MJ mm ha^{-1} hr^{-1}) (Brown and Foster, 1987) were calculated for each storm at each gage.

In summer 2004 convective storms caused five floods in Saloon Gulch and three floods in Brush Creek. For Saloon Gulch, a flood was defined as any flow that crossed the alluvial fan at the mouth of the watershed and reached the South Platte River. A flood in Brush Creek was defined as visibly turbid flow or an increase in stage that left a high water mark at the mouth of the watershed. Using these definitions, no floods occurred in either watershed in summer 2005.

The date of each flood was known from field observations in all but one case. The precipitation needed to initiate a flood was more difficult to determine because precipitation was localized and multiple storms sometimes occurred in a given day. These difficulties meant that the precipitation data were summarized using variables that would represent both: (1) the center of the largest storm on the day of a flood (maximum precipitation, maximum I_{30}, and maximum erosivity among the gages); and (2) the extent to which rainfall was distributed throughout each watershed on the day of a flood (mean precipitation, mean maximum I_{30}, and mean erosivity). The total daily precipitation, maximum I_{30}, and total daily erosivity for each gage on the days with a flood were used to determine the mean daily precipitation, maximum daily precipitation, mean maximum I_{30}, maximum I_{30}, mean erosivity and maximum erosivity within the contributing areas of the study reaches in the upper and lower portions of each watershed (Table 3). The September 2004 flood in Saloon Gulch and Brush Creek occurred while the field sites were not being regularly monitored, so this was assumed to have occurred on the day with the highest mean precipitation and mean maximum I_{30}.

At the hillslope scale about 5 mm of rain is required to initiate runoff and sediment production in the first years after a high-severity burn (Moody and Martin, 2001b; Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). The approximate I_{30} threshold for generating runoff from hillslopes and small watersheds is 10 mm hr^{-1} (Moody and Martin, 2001b; Kunze and Stednick, 2006). In the year after the Hayman fire, the erosivity threshold for hillslope sediment generation was approximately 20 MJ mm ha^{-1} hr^{-1} (Pietraszek, 2006). Given these thresholds, the number of storms (precipitation≥5 mm), intense storms (I_{30}≥10 mm hr^{-1}), and erosive storms (≥20 MJ mm ha^{-1} hr^{-1}) were determined for each gage for each summer monitoring season.

An antecedent moisture index, I_t, was calculated for each portion of the relevant watershed for the day prior to each flood by:

$$I_t = I_o(0.9)^t \qquad (2)$$

where I_o is the initial value of antecedent moisture, estimated as 25 mm on 1 June 2004, t is the number of days since the last rainfall, and 0.9 is an empirical coefficient that represents the rate of soil moisture decline (Dunne and Leopold, 1978). A lower I_t was assumed to indicate stronger soil water repellency (Doerr and Thomas, 2000; MacDonald and Huffman, 2004).

To establish whether each summer monitoring season was wetter or drier than normal, the monthly precipitation data from the Cheesman weather station in 2004 and 2005 were compared to the long-term record (n=104 years). The Cheesman station is less than 10 km southwest of the two burned watersheds and at a similar elevation, 2097 m (NOAA, 2006). To evaluate whether snowmelt runoff in March and April 2005 was greater or less than normal, discharge at the Plum Creek stream gage near Sedalia, Colorado was compared to the 20-year average (USGS, 2006). The Plum Creek watershed includes the same elevation range as Brush Creek and Saloon Gulch, and the top of the watershed is less than 10 km southeast of the two burned watersheds.

A 75 cm H-flume was installed in June 2002 in Lower Saloon Gulch and in Lower Brush Creek. The first two storms after the Hayman fire completely buried the Saloon Gulch flume and filled the Brush Creek flume with sediment, ash, and woody debris (Libohova, 2004). Although repeated efforts were made to clear the Brush Creek flume, continuous sediment deposition precluded the collection of valid streamflow data, and these efforts were abandoned in August 2003.

Crest gages were installed approximately 0.5 m downstream of the lowest cross-section in each of the confined study reaches in early July 2004, which was after the first two floods. The crest gages were wired to 1.2-cm diameter rebar pounded approximately 0.5 m into the active channel bed, but many crest gages were bent over during floods by debris. Other crest gages were buried by up to 26 cm of aggradation or left suspended by up to 18 cm of incision. The crest-gages that remained standing were often filled with sediment, and the peak stage line was lost when extracting the inner dowel from this sediment. Use of the crest gages to estimate peak flow also was hampered by the fact that the cross-section shape often changed substantially during a flood. Hence the crest gages were useful only for confirming that a flood had occurred, and could not quantify the absolute or relative magnitude of the flow. Flood lines could not reliably be used to define peak stage because there was very little ash left by summer 2004 and the resulting flood lines generally were not distinct, particularly several days after a flood.

3.3. CROSS-SECTION SURVEYS

The study reaches for intensive monitoring in the burned watershed were selected to represent a wide range of drainage scales and channel morphologies. Study reaches were stratified by scale as gullies or channels and by flow regime as ephemeral or perennial. Because all of the gullies were ephemeral, there were three drainage types: gully (G), ephemeral channel (C_E), and perennial channel (C_P). Six gully reaches and nine ephemeral channel reaches were selected for study in the Saloon Gulch watershed, whereas six perennial channel reaches were selected for study in the Brush Creek watershed. Reaches were progressively selected from the top of the watershed so that the gullies being studied drained into the channel reaches being studied (Figure 2). To the extent possible, the channel reaches were established in nearby pairs, with one reach being relatively unconfined and one reach being more confined by valley walls. Table 4 lists the number of cross-sections, reach length, contributing area, and percent of the contributing area burned at high or moderate severity for each study reach. The gully reaches had contributing areas ranging from 0.003 to 0.024 km^2. The channel reaches had contributing areas that ranged from 0.003 to 6.045 km^2.

In Saloon Gulch, the four uppermost channel reaches were in a major tributary and the five lower reaches were in the main channel (Figure 2). The six perennial reaches in Brush Creek were all in the main channel (Figure 2). The study reaches were named according to the drainage type (G, C_E, and C_P) and distance in kilometers from the uppermost study reach.

Two to five cross-sections were established 2–10 channel widths apart in each study reach, yielding 41 cross-sections in Saloon Gulch and 31 cross-sections in Brush Creek (Table 4). Each cross-section was selected to avoid confounding variables, such as woody debris or uncharacteristic boulders. The ends of each cross-section were monumented with 1.2-cm diameter rebar. One pre-fire cross-section (Libohova, 2004) in a Lower Saloon Gulch study reach was re-located and surveyed. In Brush Creek, one pre-fire cross-section was buried in the first post-fire flood, then re-established as C_P4.3 in July 2002 (Libohova, 2004); this cross-section was also included in a study reach. During the study some cross-sections had to be extended to avoid being buried by fluvial sediment or undermined by bank erosion. Each cross-section is identified by its reach name plus an alphabetical suffix beginning with “a” at the upstream cross-section.

Reach ID	Watershed	Number of cross-sections	Reach length (m)	Contrib-uting area (km^2)	Percent burned at high or moderate severity	Survey dates
G1	Saloon Gulch	3	n.d.	0.003	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
G2	Saloon Gulch	4	n.d.	0.005	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
G3	Saloon Gulch	4	n.d.	0.024	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
G4	Brush Creek	4	n.d.	0.016	100	14 June, 22 July, 10 October 2004; 25 May, 26 November 2005
G5	Brush Creek	3	n.d.	0.017	99	14 June, 22 July, 10 October 2004; 25 May, 26 November 2005
G6	Brush Creek	3	n.d.	0.017	100	14 June, 22 July, 10 October 2004; 25 May, 26 November 2005
C_E0.1	Saloon Gulch	2	15	0.003	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
C_E0.2	Saloon Gulch	3	109	0.006	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
C_E0.3	Saloon Gulch	4	199	0.063	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
C_E0.6	Saloon Gulch	4	479	0.236	100	27 May, 23 June, 3 July, 21 July, 27 July, 9 October 2004; 21 May, 13 November 2005
C_E1.8	Saloon Gulch	3	231	2.19	74	21 May, 19 June, 1 July, 16 July, 28 July, 23 October 2004; 22 May, 25 November 2005
C_E/C_P2.0	Saloon Gulch	4	95	2.32	70	21 May, 19 June, 1 July, 16 July, 28 July, 23 October 2004; 22 May, 25 November 2005
C_E2.4	Saloon Gulch	3	396	2.44	63	21 May, 19 June, 1 July, 16 July, 28 July, 23 October 2004; 22 May, 25 November 2005
C_E2.6	Saloon Gulch	3	470	3.29	55	21 May, 19 June, 1 July, 16 July, 28 July, 23 October 2004; 22 May, 25 November 2005
C_E3.1	Saloon Gulch	4	189	3.42	53	21 May, 19 June, 1 July, 16 July, 28 July, 23 October 2004; 22 May, 25 November 2005
C_P1.7	Brush Creek	2	164	3.57	96	14 June, 22 July, 10 October 2004; 25 May, 26 November 2005
C_P1.9	Brush Creek	3	276	3.61	96	14 June, 22 July, 10 October 2004; 25 May, 26 November 2005
C_P3.3	Brush Creek	5	233	5.30	76	17 June, 12 July, 26 July, 16 October 2004; 24 May, 17 July, 27 November 2005
C_P4.1	Brush Creek	4	283	5.93	67	17 June, 12 July, 26 July, 16 October 2004; 24 May, 17 July, 27 November 2005
C_P4.2	Brush Creek	4	49	6.00	67	17 June, 12 July, 26 July, 16 October 2004; 24 May, 17 July, 27 November 2005
C_P4.3	Brush Creek	3	106	6.04	66	17 June, 12 July, 26 July, 16 October 2004; 24 May, 17 July, 27 November 2005

Table 4. List of study reaches with number of cross-sections, reach length, contributing area, percent burned, and survey dates. G indicates a gully, C_E indicates an ephemeral channel, and C_P indicates a perennial channel.

The cross-sections were repeatedly surveyed with a Leica® total station, beginning at the left rebar. The goal of the surveys was to detect net incision or aggradation across the active width; the accuracy of the surveys is addressed at length in the discussion. Points were surveyed at slope breaks with a vertical resolution goal of 1 cm in gullies and 2 cm in channel reaches. Horizontal spacing was less than 1 m except for a few of the larger, planar cross-sections. For quality control, each survey was closed by surveying a designated rebar as the first and the last point. After the initial survey, a taut string between rebar endpoints was used to delineate each cross-section. The first survey took place in May or June 2004, and each cross-section was resurveyed after each flood or season (Table 4).

A survey of all cross-sections took five days. In July 2004 a second flood occurred in both watersheds before the five study reaches in Upper Brush Creek could be re-surveyed, so the data from 23 July for these five reaches represent the combined effect of two floods. Cross-sections also were re-surveyed following spring runoff in May 2005 and at the end of the study in November 2005. In July 2005 the cross-sections in Lower Brush Creek were surveyed in order to quantify the cross-sectional change caused by eight weeks of baseflows.

In October 2004 the left and right boundaries of the active channel were identified and surveyed. In May 2005, points in the thalweg upstream and downstream of each cross-section were surveyed to determine the local channel slope. These points were 2 m apart in the gully cross-sections and 10 m apart in the channel cross-sections.

The quality of the initial cross-section survey and the post-flood surveys in 2004 varied. The accuracy and reliability of the initial survey was hindered by the lack of a guide string, and the initial data from 25 of the 72 cross-sections had to be discarded due to excessive deviation from the cross-section. For these cross-sections, the second round of surveys was used as the baseline. The survey data after the 18 June 2004 flood for five cross-sections in Upper Saloon Gulch had to be removed from the dataset because the total station had been jostled and the cross-section data were inaccurate. The surveys in May, July, and November 2005 achieved the vertical resolution and horizontal spacing goals.

The true elevation for each cross-section endpoint was defined as the median elevation from the summer 2004 surveys. On average, the surveyed endpoints were within 0.3 cm of this value (s.d.=0.3 cm). Each survey was corrected for systematic errors by calculating the difference between this median rebar elevation and the surveyed elevation. This difference was distributed throughout the cross-section in proportion to the distance from the endpoint. The length of the cross-section width was corrected using a similar procedure. Points that deviated from the cross-section were shifted perpendicularly onto the cross-section using a trigonometric procedure similar to Mecklenburg (1999). This ensured that the sum of the distances between points was equal to the total distance between the rebar endpoints.

The density of points surveyed on the hillslope between the active channel and the endpoints varied among surveys. Some of the cross-section surveys in summer 2004 did not accurately represent the contours of the hillslope, so much of the calculated cross-sectional change occurred on the hillslopes, but this change was primarily an artifact of the methodology (Figure 10). To alleviate this problem, points representing the active channel boundaries in October 2004 were inserted post-facto into each survey (Figure

10). The elevations of these inserted points were defined by linear interpolation between surveyed points. This meant that each cross-section had the same active width for all surveys, the active channel was a constant distance from the left rebar, and cross-sectional change was unaffected by the variability and lower resolution of the survey points outside of the active channel. If the active channel expanded due to bank collapse after October 2004, the active channel boundaries were redefined for all surveys according to the November 2005 survey. The maximum difference in active width due to bank collapse between the October 2004 and the November 2005 surveys was 10 cm.

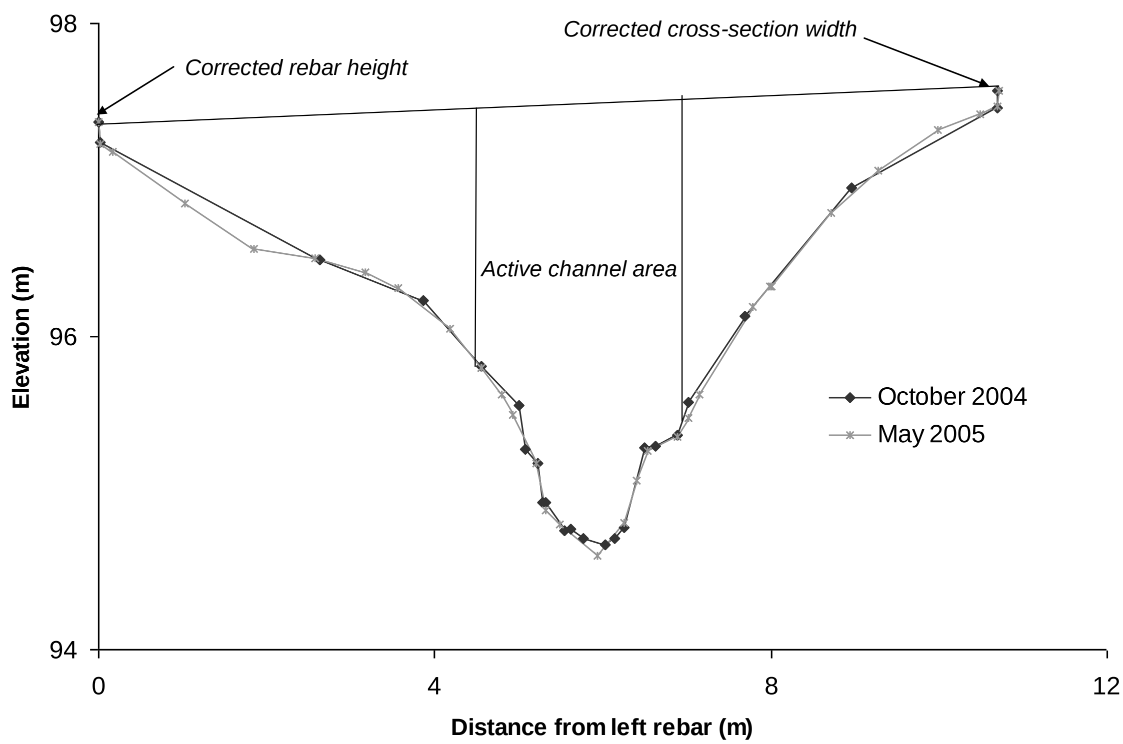


Figure 10. A cross-sectional survey from October 2004 and May 2005 showing the polygon used to determine the cross-sectional area of the active channel. The rebar heights and cross-section widths were adjusted to equal the median value from the surveys conducted in summer 2004.

The cross-sectional area of the active channel (A) was defined as a polygon with the two sides defined by the active channel boundaries, the top defined by the imaginary line between the top of the rebar endpoints, and the bottom defined by each survey of the channel bed (Figure 10). Given the variability and uncertainty in the hillslope surveys, cross-sectional change was calculated only for the active channel.

The cross-sectional area (A) was calculated for each survey, and the change in cross-sectional area (ΔA) for survey n was defined as:

$$\Delta A_n = A_{n-1} - A_n \tag{3}$$

The change in mean bed elevation (ΔMBE) was calculated by dividing the cross-sectional area by the active width (W_A) (Madej and Ozaki, 1996):

$$\Delta MBE = \Delta A / W_A \tag{4}$$

so ΔMBE values greater than zero indicate aggradation and values less than zero indicate erosion. Negative values could be due to either down-cutting or widening (i.e., erosion of the toe of the adjacent hillslope). The ΔMBE and absolute change in mean bed elevation, $|\Delta MBE|$, were calculated between each survey and for summer 2004 (21 May to 23 October 2004), winter 2004–05 (24 October 2004 to 20 May 2005), and summer 2005 (21 May to 27 November 2005).

The survey data for each cross-section were checked by superimposing the most recent survey for each cross-section on the previous survey. These graphs helped identify and correct any systematic errors such as an incorrect total station or prism height. The surveys also were graphed in plan view to determine the extent to which points deviated from the cross-section. Even with the guide string, points sometimes deviated by 10 cm or more from a straight line. In steep reaches, such a deviation could erroneously indicate aggradation or incision. If both the cross-section and plan view indicated that a given survey was unreliable, it was removed from the dataset. Twenty-five cross-sections were removed from the dataset after the initial survey, and 21 of the remaining 431 cross-section surveys were removed from the dataset. Eliminating one cross-section survey meant that ΔMBE and |ΔMBE| could not be calculated for the previous and subsequent flood, so the dataset for calculating the cross-section change due to floods was 196, and the dataset for calculating seasonal changes varied from 67 to 69 for each season.

The spatial covariance of ΔMBE between channel cross-sections for floods was evaluated by constructing a semivariogram using the mixed procedure in SAS (SAS Institute, 2002). The downstream distance of each cross-section was represented by the X coordinate, and 100,000 m were added to the downstream distance of the Brush Creek cross-sections so that the covariance between cross-sections in different watersheds would be negligible. The exponential covariance model with a nugget effect was selected on the basis of lowest Akaike's AICc (Hurvich and Tsai, 1989). The model indicated that ΔMBE was not independent between channel cross-sections separated by distances less than 148 m. A similar analysis for gullies found that ΔMBE was not independent at distances less than 8 m, which was less than the distance between some gully cross-sections. Therefore, the study reach was designated as the experimental unit, and reach means for ΔMBE and |ΔMBE| were calculated as the arithmetic average of the ΔMBE and |ΔMBE| values from all cross-sections within the reach. This reduced the dataset of cross-sectional change to 76 for floods and 21 for each season.

Empirical models were fit to reach-scale ΔMBE in gullies, ephemeral channels, and perennial channels for floods, summer 2004, winter 2004–05, and summer 2005. The purpose of the models was to evaluate the relative importance of drainage type, precipitation variables, watershed-scale variables, and reach-scale variables, and thereby to infer the physical processes that controlled reach change. Because of covariance between the independent variables, the parameter coefficients cannot be used to draw conclusions regarding the relationship between a single variable and ΔMBE.

The set of independent variables included drainage type, nine precipitation variables, two watershed-scale variables, and six reach-scale variables (Table 5). Drainage type was a categorical variable, so gully and ephemeral channel were modeled as intercept adjustments to the baseline drainage type, which was perennial channel. The other variables used in model development were continuous.

The precipitation and runoff variables considered for the floods model were mean and maximum precipitation, mean maximum and maximum I_{30}, mean and maximum erosivity, and antecedent moisture (Table 5). The precipitation variables considered for the summer 2004 and summer 2005 seasonal models were mean total precipitation and mean total erosivity. No precipitation variables were available for the winter 2004–05 model. The values for the watershed- and reach-scale variables were derived from the summer 2005 channel inventory, so they were consistent for all models.

Multivariate models of ΔMBE for summer 2004, winter 2004–05, and summer 2005 were developed in SAS using Mallow's best C(p) model selection in the REG procedure (SAS Institute, 2002). Models with all possible combinations of independent variables were fit to the data and C(p) was calculated for each model. C(p) is improved by removing variables with an F-statistic <2, so the best C(p) model may include terms that are not significant at $p<0.05$ (Ott and Longnecker, 2001). The categorical drainage type variables were automatically retained in all models regardless of statistical significance because drainage type was central to the study goals (P. Chapman, Colorado State University, pers. comm., 2006).

Variable class	Independent variable	Floods model	Summer 2004 model	Winter 2004-05 model	Summer 2005 model
Drainage type	Gully	x	x	x	x
	Ephemeral channel	x	x	x	x
Precipitation	Mean precipitation (mm)	x			
	Maximum precipitation (mm)	x			
	Mean maximum I_{30} (mm hr^{-1})	x			
	Maximum I_{30} (mm hr^{-1})	x			
	Mean erosivity (MJ mm ha^{-1} hr^{-1})	x			
	Maximum erosivity (MJ mm ha^{-1} hr^{-1})	x			
	Mean total precipitation (mm)		x		x
	Mean total erosivity (MJ mm ha^{-1} hr^{-1})		x		x
	Antecedent moisture (mm)	x			
Watershed-scale	Contributing area (km^2)	x	x	x	x
	Percent burned at high or moderate severity	x	x	x	x
Reach-scale	Active width (m)	x	x	x	x
	Depth (m)	x	x	x	x
	Slope (%)	x	x	x	x
	Width-to-depth ratio	x	x	x	x
	Slope*depth	x	x	x	x
	Confinement	x	x	x	x

Table 5. Variable classes and the independent variables used to develop empirical models of event-based and seasonal cross-sectional change.

The model for predicting ΔMBE for floods included multiple measurements of ΔMBE at the same reaches, so the MIXED procedure in SAS was used to test whether there was a significant random effect due to repeated measures. This indicated that the random effect was not significant for floods, so the coefficients for the parameters identified using Mallow's C(p) were determined using the REG procedure in SAS. For each model the coefficient of determination (R^2) and root mean square error (RMSE) were calculated. The adjusted R^2, which imposes a penalty on the R^2 based on the number of independent variables in the model, also was calculated in order to compare models with different numbers of predictive variables.

A sensitivity analysis of each model evaluated which variables were most influential by changing the value of each independent variable by one standard deviation above and below the mean. The skewed distributions of some variables meant that one standard deviation sometimes exceeded the minimum or maximum measured value, and in these cases the minimum or maximum value was used.

The variance of Studentized residuals was non-normal and non-homogeneous for models of ΔMBE for floods and winter 2004–05; this underscores the predictive limitations of the models. The non-normal prediction errors were caused by non-normal distributions for both dependent and independent variables, but square root and logarithmic transformations did not improve the fit of the residuals.

3.4. CHANNEL, TERRACE, AND HILLSLOPE MATERIAL

The bed material near one randomly-selected cross-section in each Saloon Gulch channel study reach was sampled in September 2004 and May 2005. Replicate samples were also taken at three alternate cross-sections in Upper Saloon Gulch, and three cross-sections in Lower Saloon Gulch. All of the bed material in the study reaches had been deposited or re-worked by floods after the 2002 Hayman fire. One reach in Lower Saloon Gulch was disturbed by heavy equipment during forest thinning in April 2005, so an alternate cross-section in the reach was sampled in May 2005. At each cross-section the top three cm of bed material was sampled with an 8-cm diameter ring at 10 to 20 locations systematically spaced across the channel. These samples were collected 0.5–1 m downstream of each cross-section, and the samples taken at each cross-section were composited.

The composite samples were dried at 105^{o} C for 24 hours, sieved by phi class (Φ), and weighed (Gee and Bauder, 1986). A cumulative frequency distribution was developed and used to estimate the D_5, D_{16}, D_{50}, D_{84}, and D_{95} in millimeters. Student's t-test was used to test whether the replicate samples were significantly different from the other samples from the same reaches for each of these five percentiles. Since the distributions were very similar, the mean and standard deviation for the D_5, D_{16}, D_{50}, D_{84}, and D_{95} were calculated using all fifteen samples for each sampling period. Particle sizes were converted from millimeters to phi, and the sorting index (S) was calculated by equation 5 (Folk and Ward, 1957):

$$S = \frac{\Phi_{16} - \Phi_{84}}{4} + \frac{\Phi_5 - \Phi_{95}}{6.6} \tag{5}$$

The D_{50} and sorting index were plotted against contributing area, and Student's t-test was used to test whether the D_5, D_{16}, D_{50}, D_{84}, D_{95}, and S were significantly different between the September 2004 and May 2005 samples.

In summer 2005, an additional six transects in Saloon Gulch and four transects in Brush Creek were chosen so that each would include hillslope material, a terrace that pre-dated the Hayman fire, and deposits from after the Hayman fire (Appendix H). The transects generally were within study reaches, however one location in Brush Creek between $C_P3.3$ and $C_P4.3$ was sampled because only three of the study reaches had distinct pre-fire terraces. Post-fire deposits were sampled near the edge of the active channel because this sediment is more likely to persist as a terrace than deposits closer to the low-flow channel. The top 20 cm of each deposit was sampled at 2–3 locations with a 7.5-cm diameter auger, and the samples from each deposit were composited. Each sample was processed and summarized in the same manner as the bed material described previously. The differences in each percentile between the hillslope material and the pre-fire terraces were tested using Student's t-test. Both the hillslopes and pre-fire terraces were eroded after the fire by rill and gully incision as well as channel widening. Therefore the differences in each percentile between these two sources and the post-fire deposits also were tested for significance.

Pebble counts (Wolman, 1954) were conducted in the low flow channel and the adjoining terrace downstream of three cross-sections in perennial study reach $C_P3.3$ in Brush Creek in July 2005. The goal was to determine whether streamflow since the terrace was formed in July 2004 had altered the particle-size distribution in the low flow channel relative to the terrace. The low flow channel was re-sampled in November 2005 to determine whether the bed material changed between May and November in the absence of floods. A gravelometer was used to measure the intermediate diameter of 100–120 clasts sampled from a 0.3 m x 0.3 m grid. A cumulative frequency distribution was developed and used to determine the size in millimeters of the D_5, D_{16}, D_{50}, D_{84}, and D_{95} percentiles. Because these particle-size distributions consisted of count data, two samples could be tested for differences throughout the entire particle-distribution using a single Student's t-test. Tests were conducted to compare the terrace and low flow channel in July, and the low flow channel bed between July and November.

3.5. ADDITIONAL DATA

An additional set of cross-sectional data was available from ongoing studies of rill erosion in Saloon Gulch (Pietraszek, 2006; K. Schaffrath, unpublished data). The seasonal data from these studies were used to characterize the direction and magnitude of cross-sectional change occurring in the smaller drainages above the gully reaches. The rills were all in untreated convergent swales, and the mean contributing area at the downstream cross-section was 0.19 ha (s.d.=0.20 ha). The mean slope of the rills was 26% (s.d.=3%). Five rills were measured from September 2002 to September 2006, and five more rills were added in June 2003 (Pietraszek, 2006). Each rill was measured at the beginning and end of each summer at 4–12 cross-sections (mean=6.3). Cross-sectional change was measured using a pin frame that rested directly on the rebar endpoints and bed elevations were measured to the nearest millimeter at fixed 5 cm intervals (Pietraszek, 2006). This procedure means that the rill cross-section surveys are more accurate than the cross-section surveys conducted with the total station.

4. RESULTS

4.1. PHASE I CHANGES IN THE DRAINAGE NETWORK

4.1.1. Channel Heads

In the two unburned watersheds there were only four channel heads, and these generally occurred at the confluence of two unchanneled valleys, either in the main valley or the largest tributary valley. In most cases the channels began at stable, near-vertical headcuts 10–20 cm high with continuous groundwater discharge at the base. The channel heads and banks were well vegetated, and the gravelly substrate showed some fluvial sorting within 50 m of the channel head.

The contributing area of the four channel heads ranged from 9 to 87 ha (mean=42 ha, s.d.=36 ha), and the mean downstream channel slope was 15% (s.d.=3%) (Figure 11). For three of the four channel heads the downstream slope was 1–6% less than the upstream slope. The relationship between contributing area and slope was not significant ($p>0.2$).

In the areas burned at high severity the drainage density was much greater, as headwater channels began near the top of convergent hillslopes or swales (Pietraszek, 2006). Channel heads were generally indistinct, but scour and unstable banks were obvious within 10 m downslope. The mean contributing area of the 14 channel heads was 0.05 ha (s.d.=0.04 ha), or nearly three orders of magnitude smaller than the mean value for the unburned watersheds ($p<0.0003$) (Figure 11). The mean downstream slope in the burned watersheds was 26% (s.d.=7%), and this was significantly steeper than in the unburned watersheds (p<0.0003). As in the unburned watersheds, there was no significant relationship between contributing area and slope (p=0.6). There also was not a consistent slope change at the channel heads, as the slope of the swale axes generally increases as one moves off the relatively flat ridge-tops and decreases as one approaches the higher order channels downstream. The eight channel heads with a higher downstream slope are believed to be in the convex portion of the longitudinal profile, whereas the other six channel heads are downstream of the inflection point, where the longitudinal profile becomes concave.

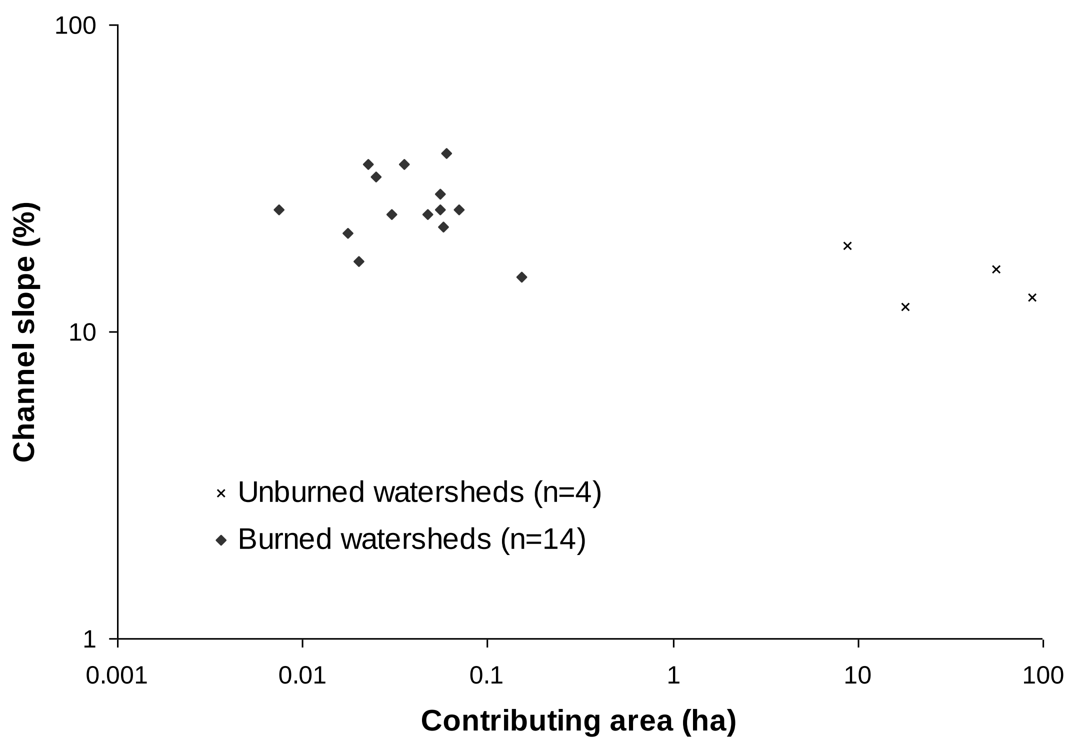


Figure 11. Channel slope vs. contributing area for the channel heads in the unburned and burned watersheds.

4.1.2. Gully-channel Transitions

The transition from an incising gully to an aggrading channel in the burned watersheds typically occurred where the channel slope flattened from a mean of 16% upstream (s.d.=3%) to a mean of 10% downstream (s.d.=2%). All but one of the 32 gully-channel transitions were associated with a decrease in slope, and the mean difference between the upstream gully slope and the downstream channel slope was 6% (s.d.=3%). This mean difference of 6% is very similar to the difference between the mean slope of the gully reaches (15%) and the mean slope of the channel reaches (8%). The contributing area above the gully-channel transitions ranged from 0.3 to 12.4 ha, and there was not a significant relationship between contributing area and either the downstream slope or the change in slope. The location of the transitions did not change during the study. Because no rapid geomorphic change was occurring in the unburned watersheds there were no obvious incising or aggrading zones, so gully-channel transitions could not be delineated.

4.1.3. Cross-sectional Change and Bed Material Change, July 2002–May 2004

The first storm after the Hayman fire (15 mm on 7 July 2002) incised rills in the formerly unchanneled convergent hillslopes in the areas that burned at high severity (Libohova, 2004). These rills continued to incise, and the mean ΔMBE for the final, relatively small storm in summer 2002 was -0.2 cm (s.d.=0.4 cm) (Pietraszek, unpublished data). The average incision due to summer storms in 2003 was 1.3 cm (s.d.=0.9 cm). Slight aggradation occurred during both winter 2002–03 and winter 2003–04, but the mean total aggradation for both winters was less than 0.1 cm (s.d.=0.1 cm). Bank collapse in 10–20% of the cross-sections caused some of the rills to become wider and shallower (Pietraszek, 2006). The net ΔMBE from September 2002 to May 2004 was -1.6 cm (s.d.=1.3 cm), but this value underestimates the total post-fire incision because the measurements only began after the first two storms.

The extreme effect of the Hayman fire on downstream channels is demonstrated by the C_E2.0d cross-section, which was established in Lower Saloon Gulch prior to the fire (Figure 12). In summer 2001 the bankfull width was 0.76 m, the bankfull depth was 0.08 m, and flow was perennial (Libohova, 2004). Between July 2001 and May 2004 sediment deposition caused the thalweg to aggrade by 1.09 m, the active channel width to increase by 13-fold to 9.17 m, and the channel depth to increase five-fold to 0.41 m (Figure 12). The cross-sectional area of post-fire deposition was 4.9 m^2, and this

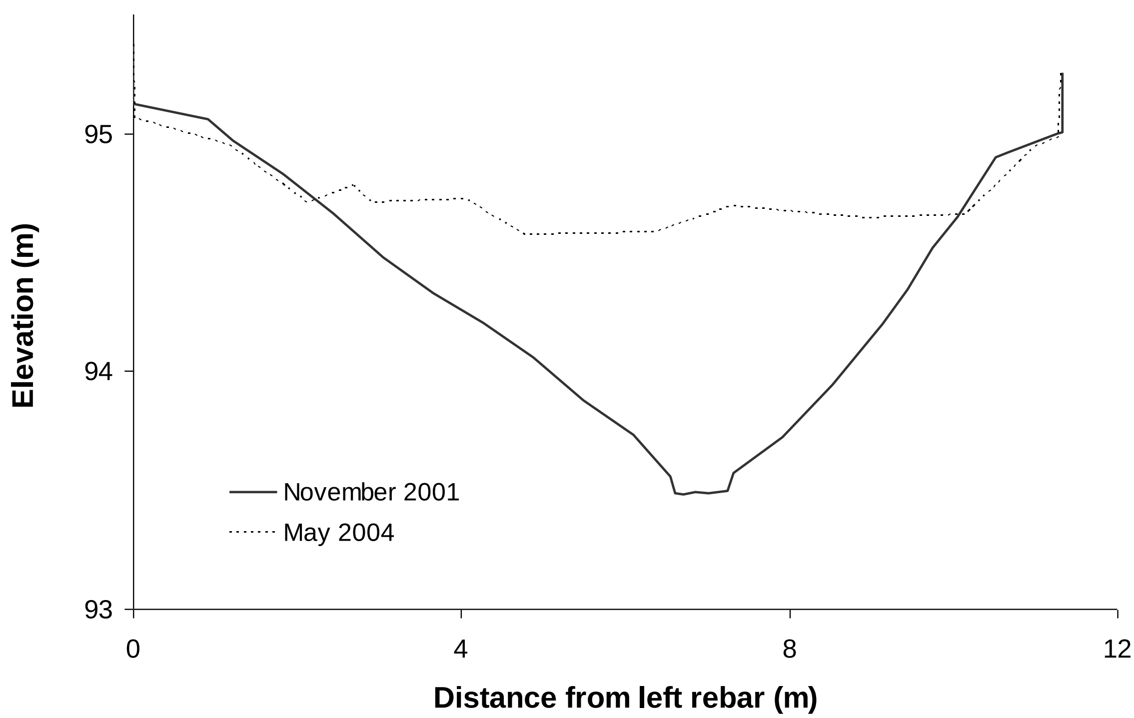


Figure 12. Cross-section data from November 2001 (pre-Hayman fire) and May 2004 for cross-section C_E2.0d in Lower Saloon Gulch.

aggradation changed the perennial surface flow to subsurface flow except during floods. The increase in channel width associated with this aggradation caused the proportion of eroding banks in a 300 m reach containing the cross-section to increase from 4% before the fire to 32% in August 2002 (Libohova, 2004). Pebble count data from summer 2001 and summer 2002 after the Hayman fire show that the reach-scale D_{50} decreased from 7 mm to 4 mm (Figure 13), the proportion of fine particles (<2 mm) increased from 9% to 29%, and the bed became less well sorted (Libohova, 2004). The bulk samples from 2004 yielded a finer and better sorted particle-size distribution than the 2002 pebble count, but these differences probably are due to the difference in sampling procedures.

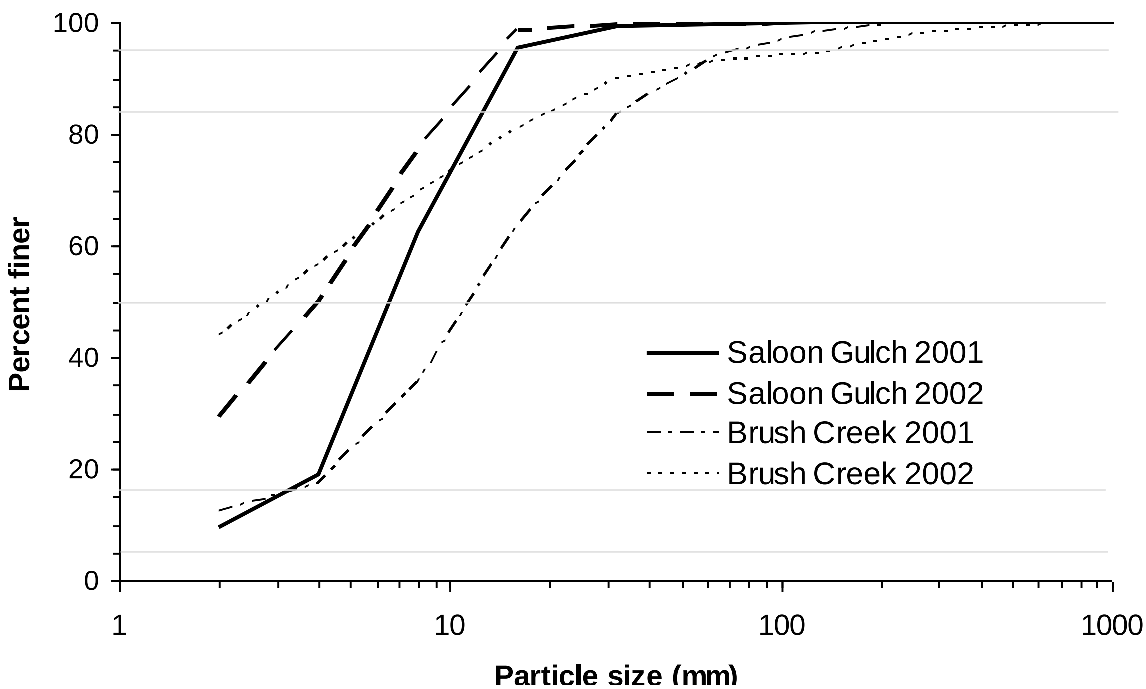


Figure 13. Particle-size distributions at the cross-sections in Lower Saloon Gulch and Brush Creek in summer 2001 and after the Hayman fire in late summer 2002 (after Libohova, 2004).

The pre-fire cross-section in Brush Creek (C_P4.3 in Figure 2) had a bankfull width of 0.67 m and a bankfull depth of 0.12 m (Libohova, 2004). A 15-mm storm on 12 July 2002 caused peak flow 1.6-m deep and up to 0.5 m of aggradation. A new cross-section established in the same reach on 21 July 2002 showed that the active channel width more than doubled to 1.52 m (Figure 14), and the depth from the top of the newly-eroded banks to the thalweg nearly tripled to 0.33 m (Libohova, 2004). Post-fire channel widening increased the proportion of eroding banks in the study reach from 13% in summer 2001 to 67% at the end of summer 2002 (Libohova, 2004). From August 2001 to September 2002 the D_{50} decreased from 12 to 3 mm (Figure 13), and the proportion of fines increased from 12% to 44% (Libohova, 2004).

From 21 July 2002 to the beginning of this study in May 2004, the active channel width at cross-section C_P4.3a in Brush Creek increased from 1.52 m to 1.87 m, and there was an additional 0.15 m of thalweg aggradation (Figure 14). The reach remained perennial despite 0.1 m^2 of additional deposition.

Figure 14. Cross-section data from July 2002 (shortly after the fire) and June 2004 for cross-section C_P4.3a in Lower Brush Creek.

4.1.4. Channel Morphology in Burned and Unburned Watersheds

The headwater erosion and downstream deposition in the burned watersheds resulted in morphological differences between the main channels in the burned and unburned watersheds. The mean proportion of unstable banks was 76% in the burned watersheds as compared to 4% in the unburned watersheds (Table 6). The lack of vegetation was one cause of the greater bank instability in the burned watersheds, as just 34% of the channel banks in the burned watersheds were well-vegetated versus nearly 100% in the unburned watersheds (Table 6). The frequency of knickpoints was 4.1 per km in the burned watersheds, and this was more than an order of magnitude higher than 0.3 knickpoints per km in the unburned watersheds (Table 6).

Variable	Burned			Unburned			Significance
	Saloon Gulch	Brush Creek	Mean	Scraggy View Gulch	Jenny Gulch	Mean	p-value
Unstable banks (% of length)	64	87	76	4	3	4	N/A
Well-vegetated banks (% of length)	30	37	34	100	99	100	N/A
Knickpoints per km	6.0	2.1	4.1	0.2	0.4	0.3	N/A
Mean active width (m)	10.6	6.1	8.4	2.2	2.1	2.2	<0.0001
Mean depth (m)	0.6	0.8	0.7	0.4	0.5	0.5	<0.0001
Mean confinement	0.34	0.47	0.41	0.27	0.24	0.25	0.003
Mean width-to-depth ratio	33	11	22	6	5	5	0.009
Surface flow (% by length)	41	83	62	43	71	57	N/A
Fine bed material (% by length)	83	52	68	53	33	43	N/A
Multiple thread channels (% by length)	16	5	11	2	4	3	N/A

Table 6. Main channel characteristics for the two watersheds that were partially burned by the Hayman wildfire and the two nearby unburned watersheds. Significance for the continuous variables refers to Student's t-tests comparing the reaches in the burned and unburned watersheds.

The high peak flows and sediment loads meant that the mean active width of the main channels in Saloon Gulch and Brush Creek were 10.6 and 6.1 m, respectively, and this was significantly more than the mean bankfull width of 2.2 m in the unburned watersheds ($p<0.0001$) (Table 6). The main channel reaches in the burned watersheds also were significantly deeper than those in the unburned watersheds ($p<0.0001$) (Table 6), but this difference was probably due more to bank cutting in the burned watersheds than channel incision. The large differences in width means that the mean width-to-depth ratio of 22 in the burned watersheds was more than four times the mean value in the unburned watersheds ($p=0.009$) (Table 6). The wider channels were the primary cause for the significantly greater confinement in the burned watersheds ($p=0.003$) (Table 6).

The percentage of the main channel with surface flow did not differ between the burned and unburned watersheds. Most of the Brush Creek and Jenny Gulch channels had surface flow, while the majority of the Saloon Gulch and Scraggy View Gulch channels did not (Table 6). When stratified by flow regime, the proportion of the channels dominated by fine bed material was 19% higher in Brush Creek than Jenny Gulch, and 30% higher in Saloon Gulch than Scraggy View Gulch (Table 6). The proportion of multiple-thread channels was 16% in Saloon Gulch and no more than 5% in the more confined Brush Creek channel and the two unburned channels (Table 6).

Within the burned watersheds, the mean valley width for the perennial main channel reaches was 10.1 m (s.d.= 7.3 m), and this was significantly less than the mean valley width of 37.6 m (s.d.=30.5 m) for the ephemeral channels ($p=0.001$). As a result, the mean channel confinement in the perennial channels was 0.64 (s.d.=0.35), which was significantly greater than the mean value of 0.35 (s.d.=0.16) for the ephemeral channels ($p<0.0001$).

4.2. PRECIPITATION AND STREAMFLOW, JUNE 2004–NOVEMBER 2005

Summer 2004 was wetter than normal; the total precipitation at Cheesman station from 1 June to 31 October was 273 mm, or 20% higher than the long-term average of 226 mm (NOAA, 2006). Over a similar time period, the mean precipitation for the six rain gages in the study area was 247 mm (s.d.=35 mm) (Table 7). The mean number of storms larger than 5 mm was 13.7 (s.d.=3.7), and the mean number of storms with an I_{30} greater than 10 mm hr^{-1} was 7.2 (s.d.=1.0). The mean I_{30} for these intense storms was 19 mm hr^{-1} (s.d.=3 mm hr^{-1}) (Table 7). For eight storms the 10 mm hr^{-1} threshold was exceeded at more than half of the rain gages in either Saloon Gulch or Brush Creek, indicating the potential for watershed-scale floods. The mean total erosivity in summer 2004 was 523 MJ mm ha^{-1} hr^{-1} (s.d.=114 MJ mm ha^{-1} hr^{-1}), which is 54% larger than the long-term annual mean of 340 MJ mm ha hr^{-1} (Renard et al., 1997).

In summer 2004 five storms caused floods in Saloon Gulch. The mean rainfall for these storms ranged from 11 mm to 18 mm, and one or more rain gages recorded at least 10 mm of precipitation, an I_{30} of at least 20 mm hr^{-1}, and an erosivity of at least 65 MJ mm ha^{-1} hr^{-1} (Table 8). Rainfall from five other storms in Saloon Gulch exceeded at least one of these values without causing a flood, but in most cases these storms had more rain but low intensity, or high intensity but little rain (Table 9).

The mean maximum I_{30} was the best predictor of floods in Saloon Gulch, as storms with a mean maximum I_{30} at least 14 mm hr^{-1} generally caused floods (Table 8). This threshold is slightly higher than the 10 mm hr^{-1} threshold identified by Moody and Martin (2001b) and Kunze and Stednick (2006) following high-severity fires in the

Dates	Mean precipitation (mm)	Mean number of storms (>5 mm)	Mean number of intense storms (I_{30} >10 mm hr^{-1})	Mean I_{30} for intense storms (mm hr^{-1})	Mean number of erosive storms (>20 MJ mm ha^{-1} hr^{-1})	Mean total erosivity (MJ mm ha^{-1} hr^{-1})
21 May-23 October 2004	247 (35)	13.7 (3.7)	7.2 (1.0)	19 (3)	6.5 (1.1)	523 (114)
21 May-27 November 2005	121 (33)	7.0 (2.9)	2.7 (2.2)	12 (1)	1.7 (1.9)	149 (121)

Table 7. Mean precipitation, number of storms, mean I_{30}, and mean erosivity for the six gages in Saloon Gulch and Brush Creek for summer 2004 and 2005. Standard deviations are in parentheses.

Date (mm/dd/yr)	Watershed	Mean precipitation (mm)	Maximum precipitation (mm)	Mean maximum I_{30} (mm hr^{-1})	Maximum I_{30} (mm hr^{-1})	Mean erosivity (MJ mm ha^{-1} hr^{-1})	Maximum erosivity (MJ mm ha^{-1} hr^{-1})	Antecedent moisture index (mm)
6/18/2004	Saloon Gulch	11	12	19	23	47	65	6
	Brush Creek*	14	14	21	25	68	87	12
6/29/2004	Saloon Gulch	15	18	23	33	71	141	35
	Brush Creek	8	8	8	9	9	10	71
7/14/2004	Saloon Gulch	18	23	33	42	161	252	27
	Brush Creek*	5	7	10	12	10	15	38
7/23/2004	Saloon Gulch	13	17	14	20	27	65	67
	Brush Creek	19	23	20	27	79	128	69
9/27/2004	Saloon Gulch	17	22	20	25	35	90	13
	Brush Creek	18	19	10	12	26	33	13

Table 8. Summary of the precipitation data for the storms that caused floods in Saloon Gulch and/or Brush Creek . The maximum values are for any one gage, and the means are for all of the rain gages in the watershed (n=3-4). * indicates that no flood occurred in that watershed.

Date (mm/dd/yr)	Mean precipitation (mm)	Maximum precipitation (mm)	Mean maximum I_{30} (mm hr^{-1})	Maximum I_{30} (mm hr^{-1})	Mean erosivity (MJ mm ha^{-1} hr^{-1})	Maximum erosivity (MJ mm ha^{-1} hr^{-1})	Antecedent moisture index (mm)
7/15/2004	7	10	12	19	25	30	46
7/16/2004	11	12	4	5	5	6	52
8/21/2004	11	13	20	25	50	76	25
9/9/2004	4	13	8	25	30	90	14
8/4/2005	20	23	8	9	15	19	5

Table 9. Summary of large storms that did not cause floods in Saloon Gulch. The maximum values are for any one gage, and the means are for all of the rain gages in the watershed (n=4).

Colorado Front Range, but 2004 was two years after burning so more vegetative recovery had taken place (Pietraszek, 2006).

The largest storm over the monitoring period occurred on 14 July 2004 in the Saloon Gulch watershed. The maximum precipitation was 23 mm, the mean maximum I_{30} was 33 mm hr^{-1}, and the mean erosivity was 161 MJ mm ha^{-1} hr^{-1}, which was more than twice the value of any other storm (Table 8; Table 9). The maximum I_{30} for this storm was 42 mm hr^{-1}, which has a 2-year recurrence interval according to the WEPP CLIGEN computer model (D. Hall, USDA Forest Service Rocky Mountain Research Station, pers. comm., 2004) and a 5-year recurrence interval according to Hershfield (1961). Like most summer storms in the region, this storm was highly spatially variable (Figure 15).

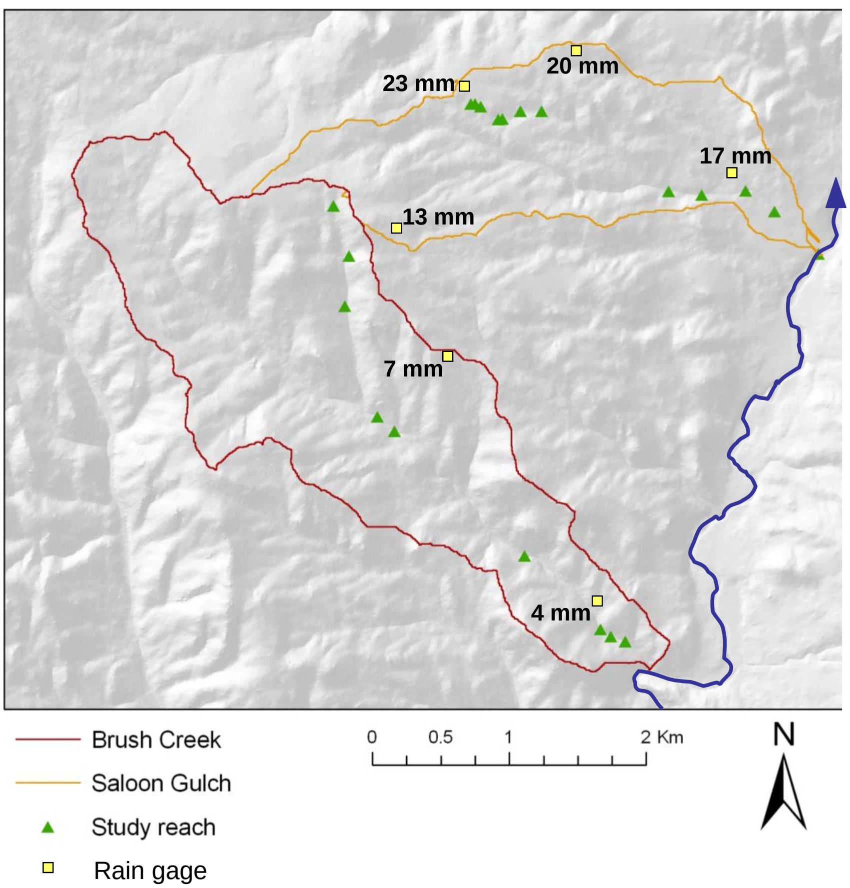


Figure 15. Measured rainfall at each rain gage for the large storm on 14 July 2004.

The floods on 18 June and 14 July 2004 were observed near the mouth of Saloon Gulch. The head of the flood on 18 June traveled at about 1 m s^{-1}, peak flow was less than 10 cm deep, and the entire flood lasted 1¼ hours. The flow was dark brown and opaque, and the bed was highly mobile. The duration of the flood on 14 July was at least two hours, and flow characteristics were similar. These two floods and the floods on 29 June and 23 July each built an alluvial fan at the outlet of Saloon Gulch that extended at least halfway across the South Platte River (Figure 16). Remnants of this fan were visible for two or three days until most of the extended fan was eroded by the South Platte River. The alluvial fan from the flood on 27 September was not observed, but the truncated remains were similar to those from previous floods.

Figure 16. Alluvial fan formed by the flood on 14 July 2004 in Saloon Gulch. This fan extended across most of the South Platte River, but most of the material was eroded away within 2-3 days, leaving a 1-2 m knickpoint.

Three storms generated floods in Brush Creek in summer 2004, and the mean precipitation ranged from 8 mm to 19 mm (Table 8). The rainfall needed to initiate floods in Brush Creek was more difficult to identify because of the smaller number of floods and rain gages in Brush Creek. The flood on 29 June was observed in the lower watershed, approximately 0.5 km upstream of the confluence with the South Platte River. At this location the leading edge of the flood traveled at about 2 m s^{-1} through the confined valley as a turbid wave approximately 30 cm high (Figure 17). A grab sample taken during peak flow had a suspended sediment concentration of 73 g L^{-1}, which is 75% higher than the maximum concentration measured one year after the Bobcat fire

Figure 17. Turbulent flood flows in Lower Brush Creek on 29 June 2004.

near Fort Collins (Kunze, 2003). The flow in Brush Creek remained turbid for one to four days after this and other floods, indicating continuing suspended sediment transport even though the discharge subsided within hours.

Discharge was not measured directly, so the mean |ΔMBE| in the Saloon Gulch study reaches was used as a relative index of flood size. The mean |ΔMBE| for the five floods in Saloon Gulch was not correlated with mean or maximum precipitation, I_{30}, or erosivity (R^2<0.01 to 0.09; p=0.6 to >0.9). Antecedent moisture had a significant inverse correlation with |ΔMBE| (R^2=0.79; p=0.04) (Figure 18). The tendency for flood size to increase under drier conditions suggests that hillslope soil water repellency was an important control on runoff.

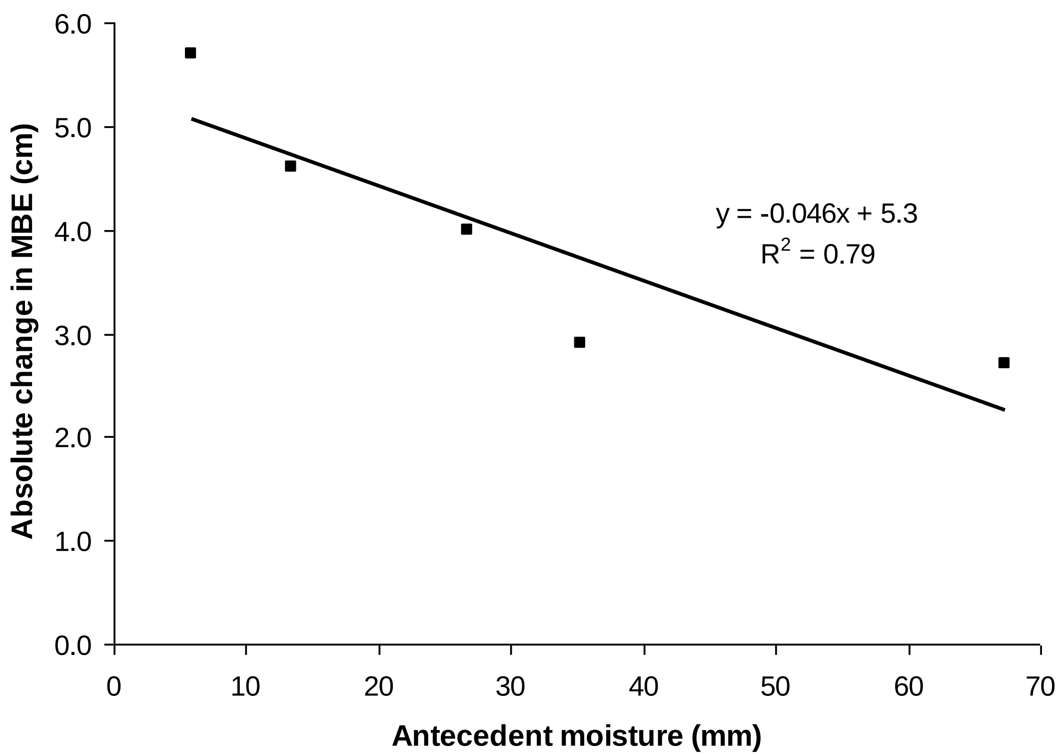


Figure 18. Absolute change in mean bed elevation vs. antecedent moisture in Saloon Gulch for five floods in summer 2004.

From 1 November 2004 to 31 May 2005 precipitation at Cheesman station was 33% greater than the 104-year average of 177 mm, and snowfall was 46% above the mean of 126 cm (NOAA, 2006). The snowpack was 12–30 cm deep when the study sites were visited in late December and early April. At the Plum Creek gage snowmelt discharge for April and May 2005 was 220% of the 20-year average (USGS, 2006).

The largest storm of the winter was 26 mm on 25 April, and this had a maximum I_{30} of 10.6 mm hr^{-1}. This storm was the likely cause of surface flow in the gullies, which was documented by crest gages in both watersheds. The only evidence of over-winter flow in the ephemeral study channels was the formation of braided rivulets in two reaches where the Saloon Gulch valley abruptly widened. These rivulets were only 1–10 cm wide and less than 10 cm deep, and occupied less than 5% of the active channel area. Small mounds of sediment indicated where these rivulets had infiltrated into the alluvium.

In the most confined reach in Lower Saloon Gulch (C_E2.0 in Figure 2), runoff from snowmelt and the April storm was sufficient to incise a channel that was up to 3.6 m wide and 1.4 m deep (Figure 19). This incision caused flows to change from ephemeral to perennial, but the water then infiltrated back into the unconsolidated alluvium less than 50 m downstream, leaving a convex deposit across the 10-m wide active channel.

Baseflow was observed in Lower Brush Creek during the two winter field visits, and the crest gages confirmed the absence of large winter floods. Although the ambient temperature was below freezing during the field visits, the banks of Brush Creek were erodible because they were not stabilized by interstitial ice, and the bed material was highly mobile.

Figure 19. Snowmelt runoff incised a deep channel into post-fire deposits in reach C_E2.0, which was the narrowest reach in Lower Saloon Gulch. This incision caused a shift in the flow regime from ephemeral to perennial.

Summer 2005 was relatively dry; the total precipitation at Cheesman from 1 June to 30 November was only 172 mm or 70% of the long-term mean. The mean precipitation in the study area was just 121 mm for the summer 2005 monitoring season (s.d.=33 mm) (Table 7). The mean number of storms larger than 5 mm was 7.0 (s.d.=2.9) as compared to nearly 14 in 2004. The mean number of storms with an I_{30} larger than 10 mm hr^{-1} was only 2.7 (s.d.=2.2), or less than one-third of the mean value for summer 2004. The mean I_{30} for these intense storms was only 12 mm hr^{-1} (s.d.=1 mm hr^{-1}), and the only storm that exceeded 10 mm hr^{-1} at more than half of the rain gages in a watershed was centered on the lower, unburned portion of the Brush Creek watershed. The mean summer erosivity was 149 MJ mm ha^{-1} hr^{-1} (s.d.=121 MJ mm ha^{-1} hr^{-1}), or just 44% of the long term mean (Renard et al., 1997).

None of the storms in summer 2005 caused a flood in either of the study watersheds. The crest gages recorded no surface flow in the ephemeral study reaches in Saloon Gulch, although surface flow was present for about 50 m in the newly perennial reach. Flows in Brush Creek remained low and clear throughout the summer, and the crest gages recorded no floods. The bed material appeared to be less mobile in summer 2005 than during either summer 2004 or the winter, and bed material movement was more sporadic and localized.

4.3. CROSS-SECTIONAL AND PARTICLE SIZE CHANGES IN THE BURNED WATERSHEDS, JUNE 2004–NOVEMBER 2005

4.3.1. Summer 2004

The wet summer of 2004 generally caused incision in the rills and gullies in the burned watersheds, and aggradation in the ephemeral and perennial channels (Figure 20). The rills incised an average of 1.4 cm (s.d.=0.9 cm), although localized aggradation occurred at 8% of the cross-sections (Figure 21a; Table 10). There was no significant relationship between reach-mean ΔMBE for the rills and either slope or contributing area.

The average ΔMBE for the six gully reaches in summer 2004 was -1.0 cm (s.d.=2.3 cm), or slightly less than for the rills (Figure 20). Four of the six gully reaches incised an average of 2.0 cm whereas the other two aggraded an average of 1.2 cm (Figure 21b; Table 10). Ten of the 21 cross-sections aggraded, but small retreating knickpoints caused 5.6 cm of erosion at four cross-sections in reaches G3 and G5, and this incision dominated the reach-scale response. There was no significant relationship between reach-scale ΔMBE and slope or contributing area.

On a storm-by-storm basis the gully cross-sections incised during some storms and aggraded during others. Individual cross-sections incised 42% of the time and aggraded 58% of the time. However, the mean response among the gully reaches was incision for four of the five floods (Figure 22) because the magnitude of incision was generally greater than the magnitude of aggradation.

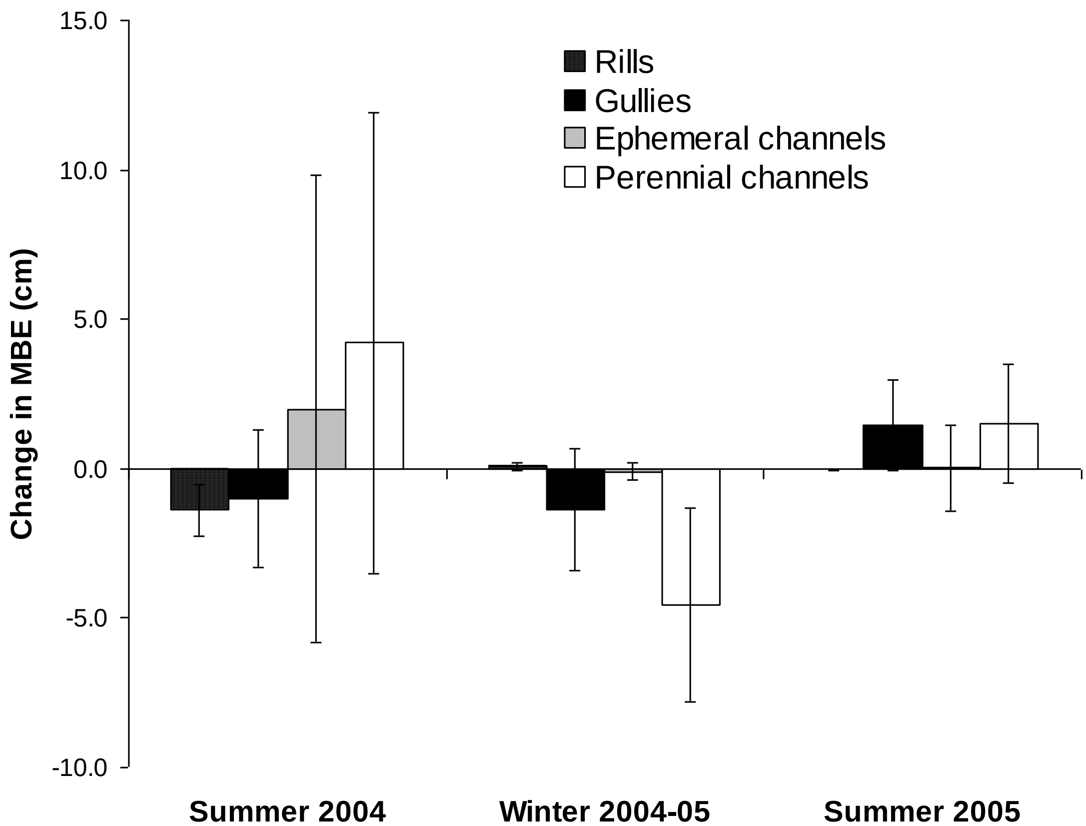


Figure 20. Change in mean bed elevation for each drainage type by season. Bars represent one standard deviation.

Catchment	Reach ID	Change in mean bed elevation (cm)								
		Summer 2004			Winter 2004-05			Summer 2005		
		Reach mean	Minimum cross-sectional change	Maximum cross-sectional change	Reach mean	Minimum cross-sectional change	Maximum cross-sectional change	Reach mean	Minimum cross-sectional change	Maximum cross-sectional change
Saloon Gulch	R1	-1.3	-2.0	0.1	0.0	0.0	0.1	-0.1	-0.1	0.0
Saloon Gulch	R2	-2.6	-6.9	-1.0	0.3	-1.5	1.6	0.0	-0.1	0.1
Saloon Gulch	R3	-0.9	-1.9	0.7	0.2	0.0	1.5	0.0	-0.1	0.1
Saloon Gulch	R4	-0.8	-2.0	0.4	0.0	-0.1	0.1	0.0	0.0	0.1
Saloon Gulch	R5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0	-0.1	0.1
Saloon Gulch	R6	-1.2	-1.8	-0.4	0.1	0.0	0.1	-0.1	-0.1	0.0
Saloon Gulch	R7	-1.0	-2.3	0.7	0.0	-0.1	0.1	-0.1	-0.2	0.0
Saloon Gulch	R8	-2.8	-4.8	-1.1	0.0	0.0	0.1	0.0	-0.1	0.1
Saloon Gulch	R9	-1.8	-2.5	-1.3	0.0	-0.1	0.1	0.0	-0.2	0.0
Saloon Gulch	R10	-0.2	-0.3	0.0	0.0	-0.1	0.0	0.0	-0.1	0.0
Saloon Gulch	G1	-0.4	-4.1	2.8	-1.3	-2.6	-0.5	1.5	0.8	2.6
Saloon Gulch	G2	-0.1	-2.9	3.1	-1.2	-2.7	0.3	1.4	0.4	2.4
Saloon Gulch	G3	-4.4	-7.0	-2.1	0.8	0.0	1.2	0.1	-0.9	1.5
Brush Creek	G4	1.3	-0.6	3.4	-0.8	-1.8	-0.2	0.3	-0.1	0.8
Brush Creek	G5	-3.3	-7.3	0.7	-5.3	-7.2	-3.3	4.3	2.8	5.9
Brush Creek	G6	1.1	0.4	1.8	-0.5	-3.3	1.7	1.1	-0.2	3.2
Saloon Gulch	C_E0.1	0.4	-1.2	2.1	0.1	-1.2	1.4	-1.2	-1.5	-0.9
Saloon Gulch	C_E0.2	1.4	0.2	3.4	-0.3	-1.9	0.8	0.4	-0.2	1.1
Saloon Gulch	C_E0.3	-4.5	-12.7	-0.2	-0.3	-1.2	1.3	1.9	1.2	2.7
Saloon Gulch	C_E0.6	-5.6	-7.3	-3.8	-0.3	-0.5	-0.2	1.3	1.1	1.6
Saloon Gulch	C_E1.8	6.1	4.4	7.1	0.3	-0.3	0.6	-0.9	-3.0	0.7
Saloon Gulch	C_E/C_P2.0	20.1	12.6	27.5	-8.8	-30.8	8.0	6.0	-15.7	40.5
Saloon Gulch	C_E2.4	2.2	-0.1	6.6	-1.5	-4.4	0.1	1.6	1.4	1.8
Saloon Gulch	C_E2.6	1.6	0.2	3.0	0.2	-1.5	1.1	-1.6	-2.6	-0.8
Saloon Gulch	C_E3.1	-3.9	-9.9	-0.5	-0.5	-4.7	3.6	-1.3	-2.6	0.0
Brush Creek	C_P1.7	-1.0	-1.2	-0.8	-3.0	-3.2	-2.8	1.1	-0.5	2.8
Brush Creek	C_P1.9	12.4	0.6	19.5	-1.7	-11.0	3.2	0.4	-0.4	1.9
Brush Creek	C_P3.3	15.1	-1.3	24.3	-6.0	-11.0	-2.2	0.3	-2.6	2.2
Brush Creek	C_P4.1	-0.8	-5.4	2.1	-4.4	-5.4	-3.5	1.4	0.9	2.0
Brush Creek	C_P4.2	-3.0	-18.7	5.1	-8.0	-16.3	0.3	0.7	-0.3	1.4
Brush Creek	C_P4.3	2.3	2.2	2.4	0.0	-1.0	1.5	0.8	-0.4	1.5

Table 10. Mean, minimum and maximum seasonal change in mean bed elevation for the rill, gully, ephemeral and perennial channel study reaches; n.d. indicates no data.

The largest and most erosive storm on 14 July caused all of the gullies to aggrade an average of 1.8 cm (s.d.=0.2 cm). This aggradation was probably due to the relatively large amount of incision in the upstream rills, and the resulting sediment load overwhelmed the transport capacity of the gullies. There was no significant relationship between the mean ΔMBE or |ΔMBE| in the gullies and storm magnitude, intensity, or erosivity.

In summer 2004 the pattern of change in the ephemeral channels is best described as sediment redistribution. The mean ΔMBE among the nine ephemeral channel reaches was 2.0 cm (s.d.=7.8 cm) (Figure 20), but six reaches aggraded an average of 5.3 cm and three reaches incised an average of 4.7 cm (Figure 21c; Table 10). The maximum aggradation was 20.1 cm in reach C_E2.0, probably because the channel slope in this reach was only 6% as compared to a mean of 10% for the other eight ephemeral channel reaches. The direction of seasonal change in ΔMBE was generally consistent for the cross sections within a reach, although the magnitude varied (Figure 21c). There was no significant relationship between reach ΔMBE and channel slope or contributing area.

For individual floods, the ΔMBE in ephemeral channels was spatially and temporally variable. For example, the flood on 23 July caused four ephemeral channel reaches to aggrade and five reaches to incise (Figure 23). The next flood on 27 September was caused by a similar storm (Table 8), but five of the nine reaches had the opposite response to the 27 September flood relative to the 23 July flood (Figure 23). The high variability in the direction and magnitude of ΔMBE among the reaches is partly due to the varying inflows of water and sediment from tributaries in response to the localized nature of the rainstorms as well the highly sporadic knickpoint retreat.

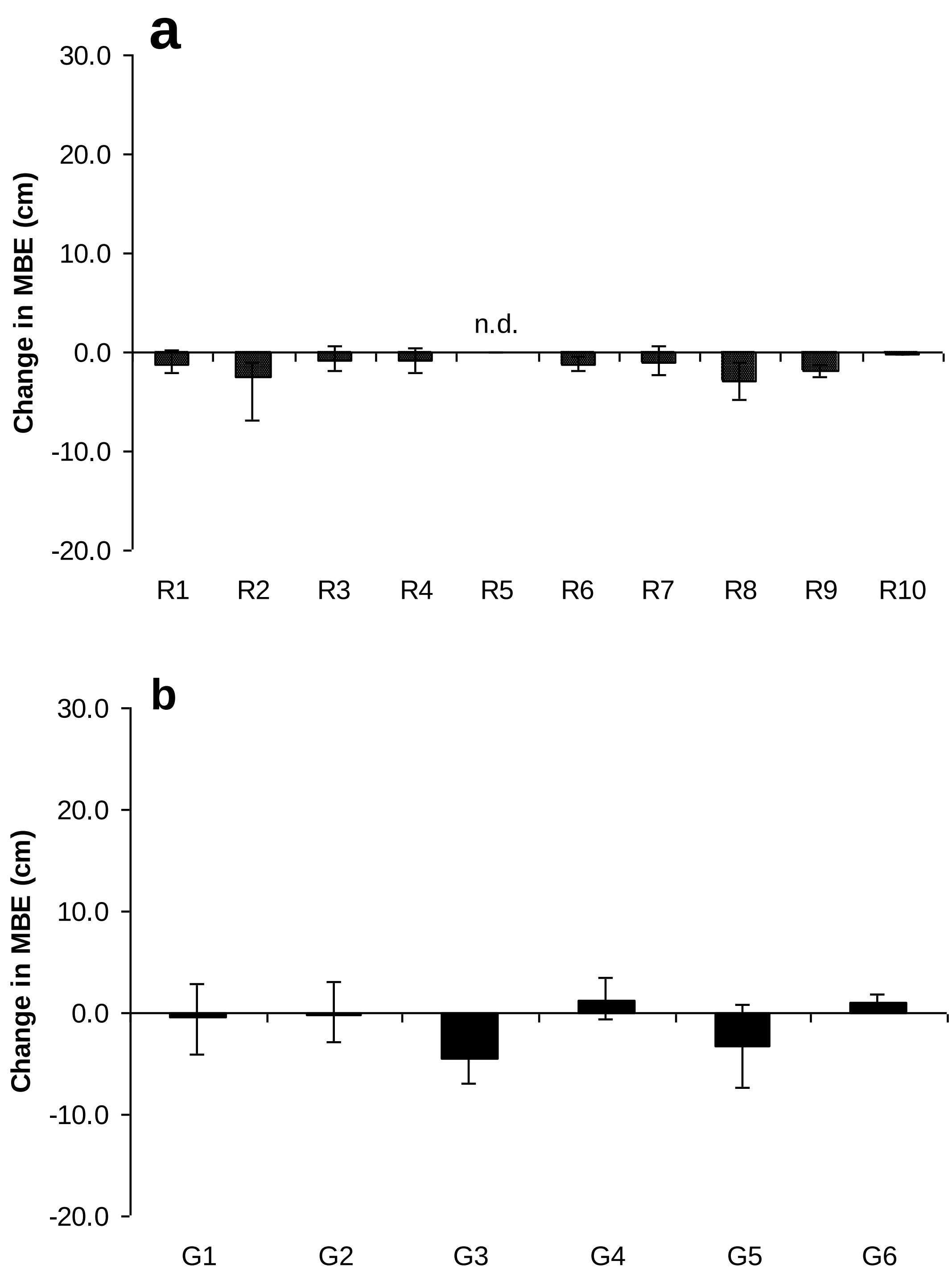
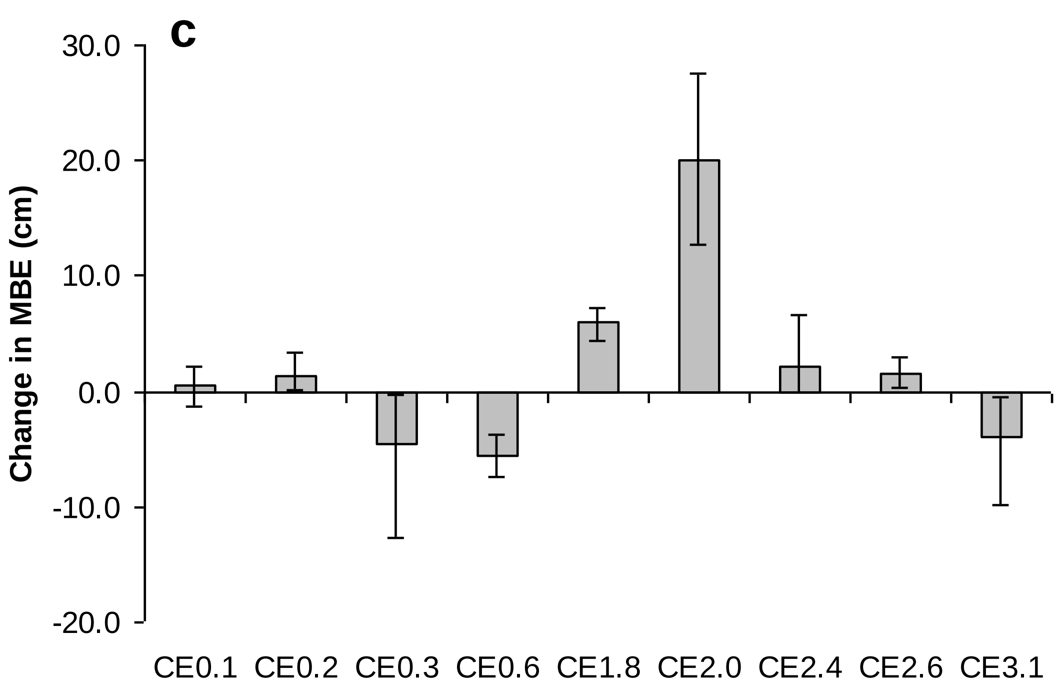
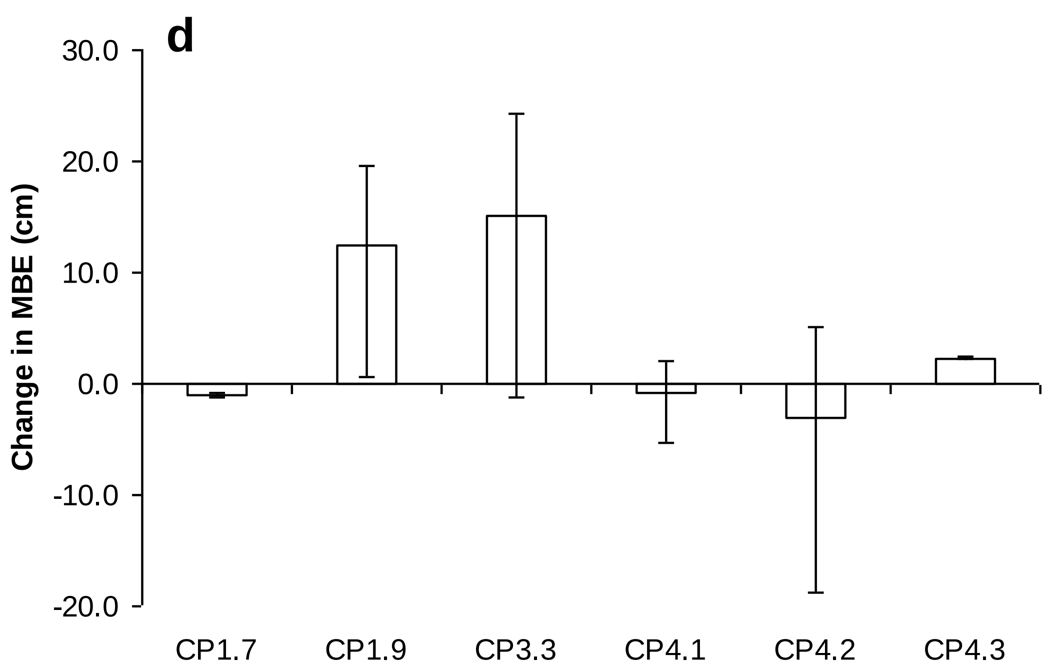


Figure 21. Change in mean bed elevation in summer 2004 for: (a) rill reaches; (b) gully reaches; (c) ephemeral channel reaches; and (d) perennial channel reaches. Bars represent minimum and maximum change at individual cross-sections; “n.d.” indicates no data.


c
30.0
20.0
10.0
0.0
-10.0
-20.0
Change in MBE (cm)
CE0.1 CE0.2 CE0.3 CE0.6 CE1.8 CE2.0 CE2.4 CE2.6 CE3.1


d
30.0
20.0
10.0
0.0
-10.0
-20.0
Change in MBE (cm)
CP1.7 CP1.9 CP3.3 CP4.1 CP4.2 CP4.3

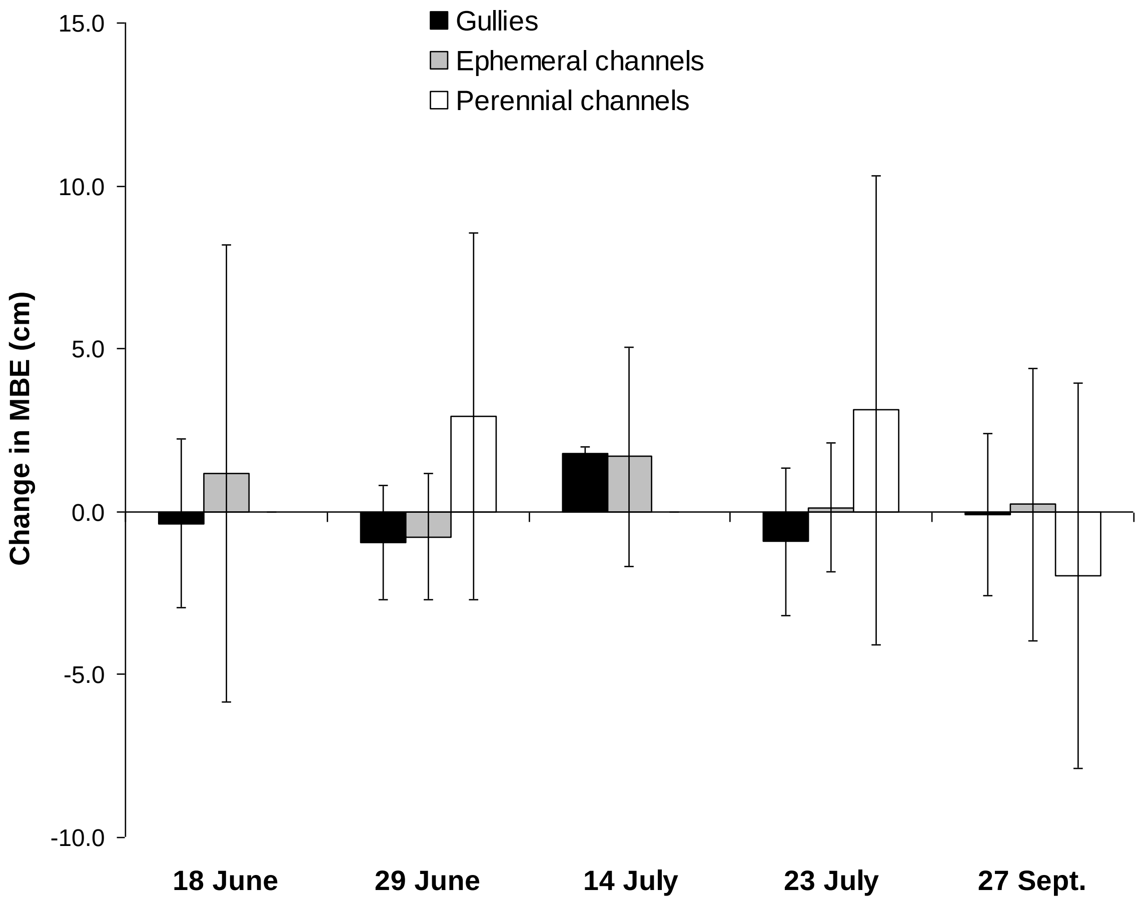


Figure 22. Change in mean bed elevation for gullies, ephemeral and perennial channels for the five floods in summer 2004. There are no data for perennial channels for the 18 June and 14 July storms because these did not cause floods in Brush Creek. Bars represent one standard deviation.

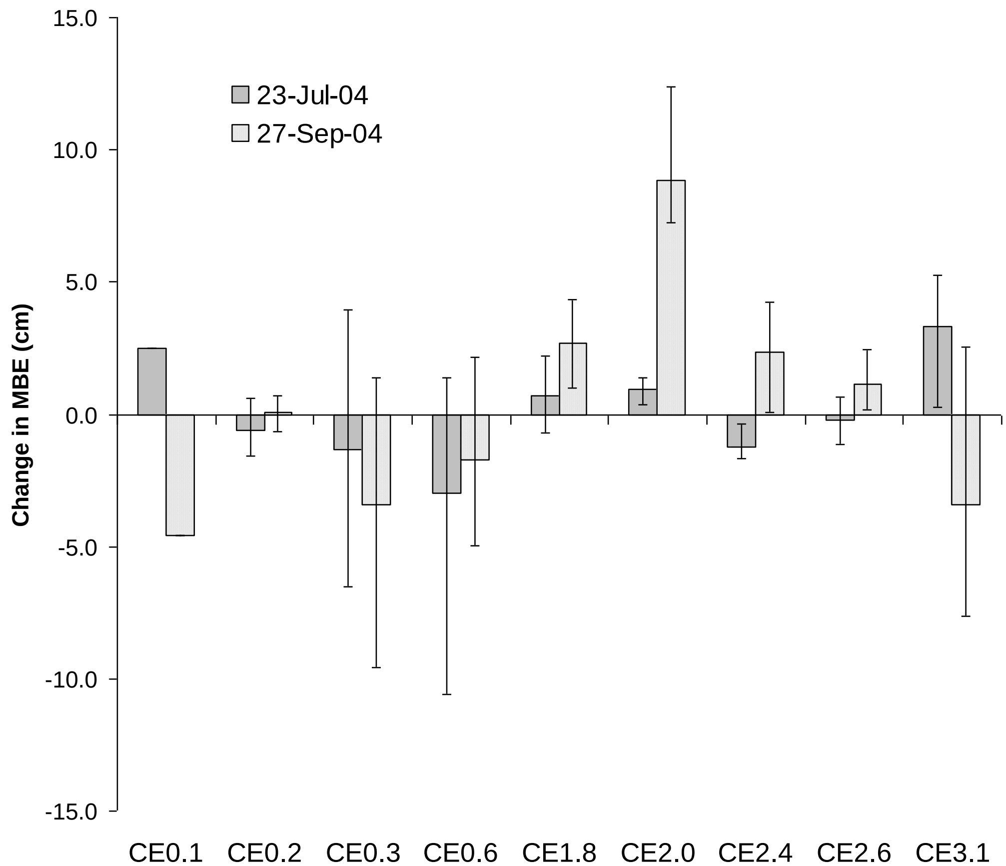


Figure 23. Change in mean bed elevation for the ephemeral channel reaches for two similar storms in summer 2004. Bars represent the minimum and maximum change for individual cross-sections within each reach. No bars are shown for $C_E0.1$ because one of the two cross-sections in the reach was discarded for each of these storms.

On a storm-by-storm basis, the direction and magnitude of ΔMBE also varied among the cross-sections within each ephemeral channel reach (Figure 23). Both incising and aggrading cross-sections were observed in five of the nine study reaches as a result of the 23 July flood, and four reaches had both incising and aggrading cross-sections in the 27 September flood. The standard deviation of the cross-section response within a reach was 60% greater than the reach mean ΔMBE for the 23 July flood and twice the mean ΔMBE for the 27 September flood.

In summer 2004 the mean ΔMBE for the six perennial study reaches in Brush Creek was 3.5 cm (s.d.=8.1 cm) (Figure 20). There was considerable variability between reaches, as three reaches aggraded an average of 9.9 cm (s.d.=6.7 cm) and three reaches incised an average of 1.6 cm (s.d.=1.2 cm) (Figure 21d; Table 10). Most of the aggradation occurred in reaches C_P1.9 and C_P3.3 (12.4 and 15.1 cm, respectively) because these reaches were less confined and reach C_P3.3 was less steep. Over the three floods there was not a consistent tendency for a given perennial reach to either aggrade or incise. The ΔMBE for summer 2004 was not significantly correlated with either slope or contributing area. Cross-sectional change was not necessarily consistent within a reach, even on a seasonal basis, as half of the reaches contained both aggrading and incising cross-sections (Figure 21d).

Although the mean ΔMBE among the ephemeral and perennial channels was aggradation for summer 2004, most of this aggradation was concentrated in C_E2.0, C_P1.9, and C_P3.3 (Figure 21). The 14–20 cm of aggradation in these three “storage” reaches effectively controlled the overall direction of the mean ΔMBE for the ephemeral and perennial channels; the other eight ephemeral and four perennial reaches incised an average of 0.3 and 0.6 cm, respectively (s.d.=4.0, s.d.=2.1 cm). The three storage reaches had significantly lower slopes (p=0.02) and generally were less confined than the other channel reaches, and this probably explains their extensive aggradation in summer 2004.

The variations in incision and aggradation observed in summer 2004 indicate that each flood re-worked the bed material in Saloon Gulch. Between early September 2004 and May 2005 the only widespread surface flow was caused by the flood on 27 September, but over this period the D_5, D_{16}, D_{50}, and D_{95} in the ephemeral channel reaches significantly coarsened (p=0.001 to 0.04) (Figure 24). This coarsening indicates either that the flood on 27 September delivered less fine sediment to the ephemeral channels than previous floods, or that this flood preferentially eroded the finer particles, or both.

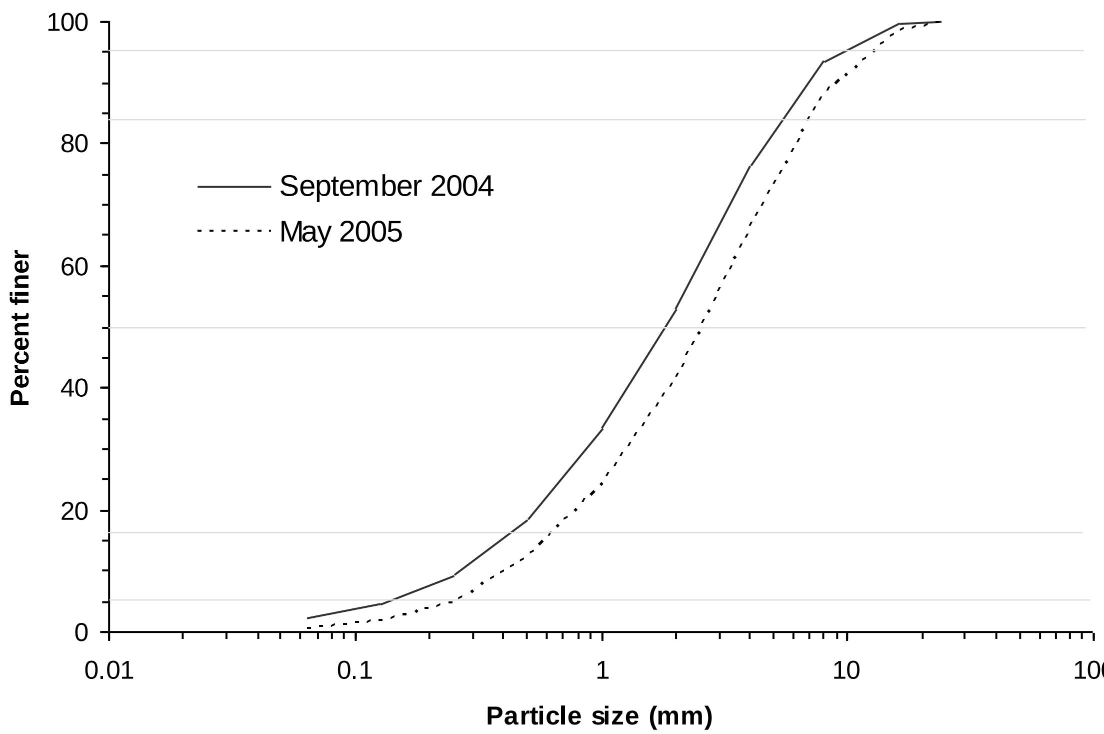


Figure 24. Particle-size distributions of bed material samples from the ephemeral channel study reaches in Saloon Gulch in September 2004 and May 2005.

Both field observations and the cross-section data from 2001 through 2004 confirm that post-fire floods from summer 2002 through 2004 caused extensive deposition in all of the ephemeral reaches and most of the perennial reaches. This sediment was derived from the hillslopes and pre-fire terraces, and the bulk samples from these two sources had very similar particle-size distributions (Figure 25). The sediment deposited after the Hayman fire was better sorted and had significantly fewer fine particles than the material from the hillslopes and pre-fire terraces ($p<0.01$ for the D_5 and D_{16}) (Figure 25). The differences in the fine fraction of the particle size distribution between the post-fire deposits and the two source materials indicate that the post-fire floods were removing some of the finer particles from the watershed.

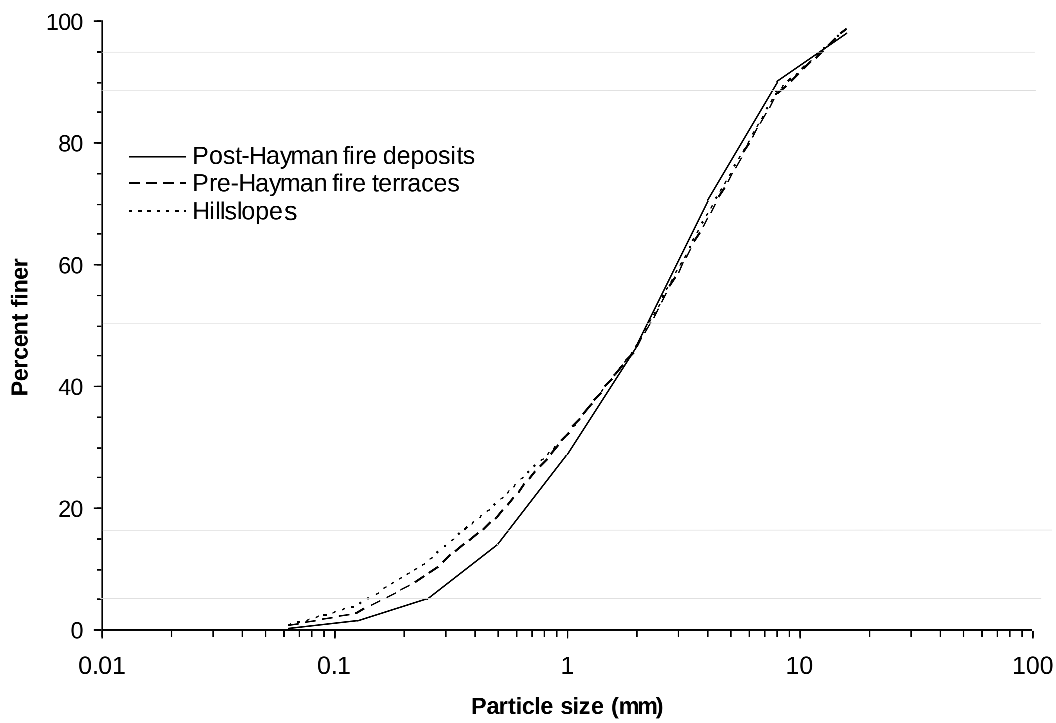


Figure 25. Particle-size distribution of bulk samples from the post-Hayman fire deposits in the ephemeral and perennial channels, the pre-Hayman fire terraces, and the adjacent hillslopes.

4.3.2. Winter 2004–05

Channel change between October 2004 and May 2005 was due to the combined effect of winter baseflows, snowmelt runoff, and the storm on 25 April. The crest gages showed evidence of surface flow in the gullies but not in the rills or ephemeral channels, and this flow probably occurred as a result of the 25 April storm. Over the entire winter the rills aggraded slightly, the gullies and perennial channels incised, and there was no measurable change in the ephemeral channels (Figure 20).

The mean ΔMBE in the rills was only 0.1 cm (s.d.=0.1 cm) (Figure 20). Three of the rill reaches aggraded from 0.1 to 0.3 cm, and there was no measurable change in the remaining six reaches. These measurements are believed to be accurate to within 1 mm due to the use of a pin frame. Two-thirds of the rill reaches also had at least one cross-section that slightly incised (Figure 26a; Table 10). ΔMBE had a significant positive correlation with contributing area (R^2=0.52; p=0.03) due to aggradation in two rills with large contributing areas. ΔMBE was not significantly related to reach slope.

There was much more cross-sectional change in the gully reaches during winter 2004–05, as five of the six gully reaches incised and the overall mean ΔMBE was -1.4 cm (s.d.=2.0 cm) (Figure 20). Much of the overall incision came from the 5.3 cm of incision in reach G5 (Figure 26b; Table 10), where a knickpoint retreated through one of the three cross-sections. The average ΔMBE in the other reaches was only -0.6 cm (s.d.=0.8 cm). For half of the reaches incision occurred at each cross-section, whereas the other reaches had both incising and aggrading cross-sections (Figure 26b). The steeper reaches generally had more incision (R^2=0.59), but this was only marginally significant (p=0.09). There was no significant relationship between ΔMBE and contributing area.

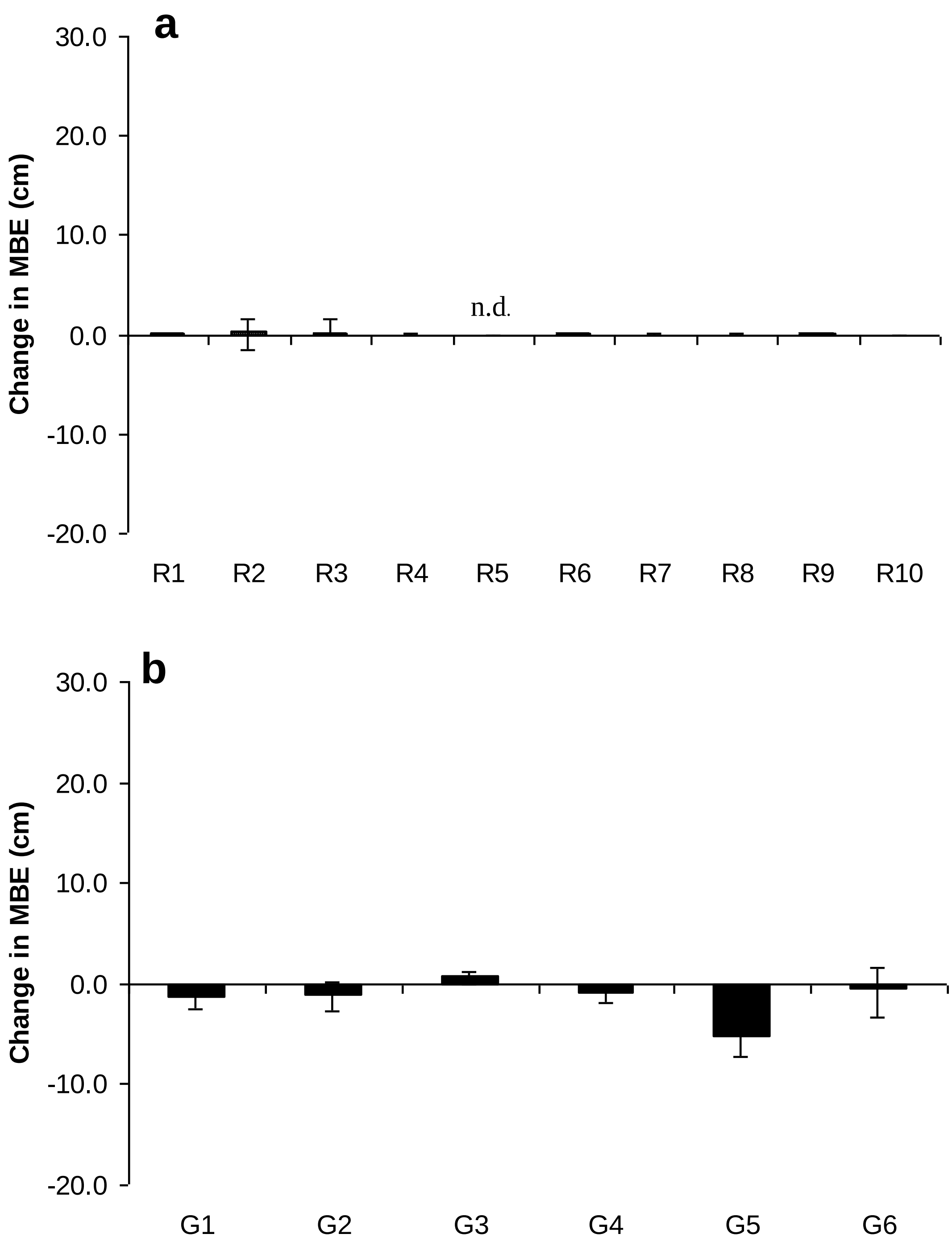
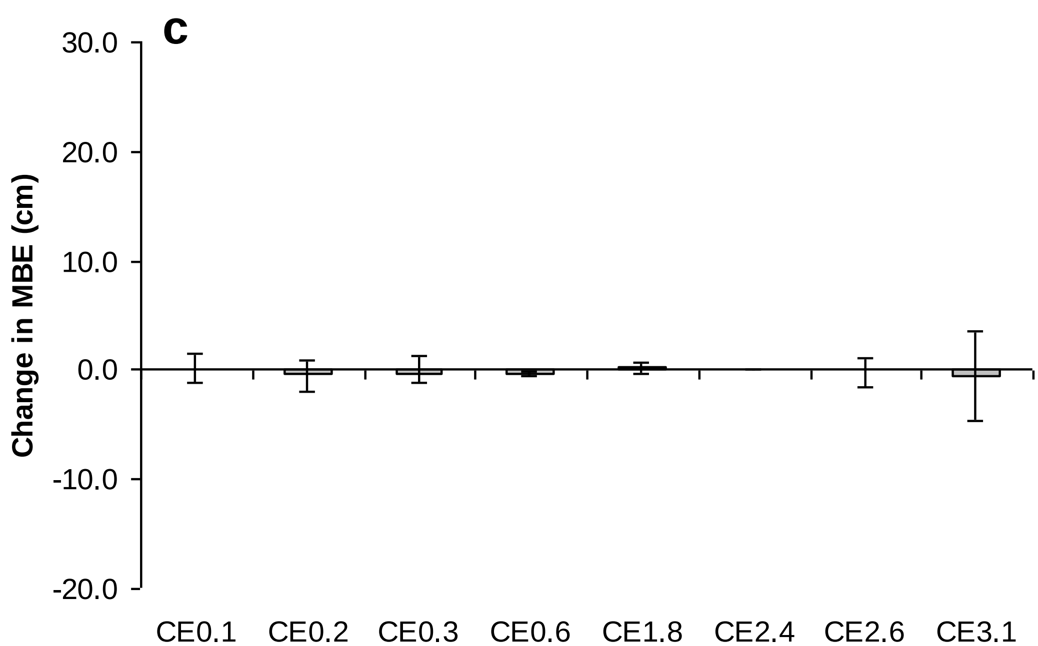
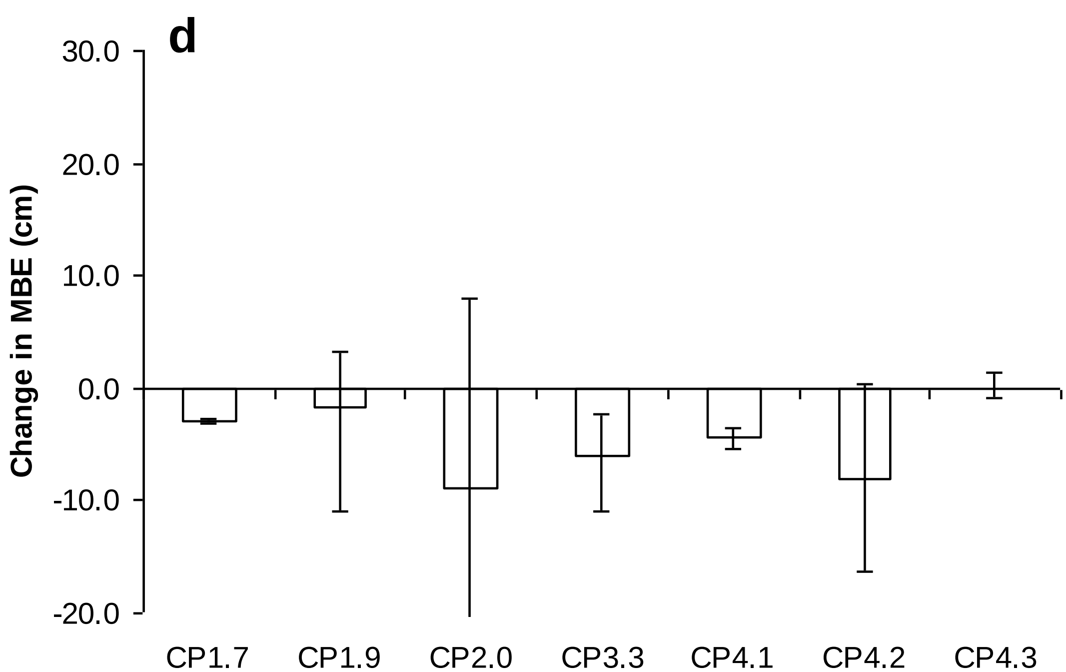


Figure 26. Change in mean bed elevation in winter 2004-05 for: (a) rill reaches; (b) gully reaches; (c) ephemeral channel reaches; and (d) perennial channel reaches. Bars represent minimum and maximum change at individual cross-sections; "n.d." indicates no data.


c
Change in MBE (cm)
30.0
20.0
10.0
0.0
-10.0
-20.0
CE0.1
CE0.2
CE0.3
CE0.6
CE1.8
CE2.4
CE2.6
CE3.1


d
Change in MBE (cm)
30.0
20.0
10.0
0.0
-10.0
-20.0
CP1.7
CP1.9
CP2.0
CP3.3
CP4.1
CP4.2
CP4.3

The incision in the gullies over winter 2004–05 is surprising because the rills showed either no change or slight aggradation. The largest storm over this period was 26 mm of rain on 25 April with a maximum intensity of 10.6 mm hr^{-1}. Although this intensity was lower than the 14 mm hr^{-1} threshold for flooding in Saloon Gulch observed in summer 2004, the soils were quite wet due to snowmelt and 9 mm of precipitation on the previous day. The rills did not incise but the gullies did, which suggests that surface flow began downstream of most of the rill cross-sections. Because little sediment was transported into the gullies, 68% of the gully cross-sections incised over the winter as compared to just 42% in response to floods in summer 2004.

In the ephemeral channel reaches there was little change in ΔMBE during the winter of 2004–05 (Figure 20). Surface flow was limited to braided rivulets in two reaches, and these rivulets did not cause any measurable incision at the reach scale. The mean ΔMBE was only -0.1 cm (s.d.=0.3 cm), which is less than the measurement error of the total station surveys.

The largest changes were in reach C_E3.1, which includes the mouth of the Saloon Gulch watershed. The four cross-sections in this reach incised as much as 4.7 cm and aggraded as much as 3.6 cm (Figure 26c; Table 10). This reach had three distinct channels, each with high, unstable banks; bank slumping is believed to be the cause of much of this change. Measurement errors also may be higher in this reach because the large width of the active channel (50–75 m) and lack of vantage points necessitated multiple total station locations for each cross-section. No surface flow was recorded by the crest gage in this reach, indicating that little or no sediment was exported from this reach and hence from the Saloon Gulch watershed during the winter. In reach C_E2.0 a groundwater seep incised a channel and initiated perennial surface flow, so this reach was re-classified as perennial for winter 2004–05 and summer 2005.

The six perennial reaches in Brush Creek and the newly-perennial reach in Saloon Gulch generally incised from November 2004 to May 2005, although one reach had no measurable change (Figure 26d; Table 10). The average ΔMBE was -4.6 cm (s.d.=3.3 cm) (Figure 20), and in most cross-sections the incision was concentrated in the low flow channel. The direction of change was far more consistent than in the previous summer, as six of the seven of the perennial reaches incised (Figures 20d: Figure 25d; Table 10). There was no significant relationship between ΔMBE and reach slope or contributing area.

Two of the three storage reaches identified in summer 2004 had localized zones of both extensive incision and aggradation. In the newly perennial reach in Saloon Gulch, C_P2.0, snowmelt runoff incised a low flow channel that was 3.6 m wide and 1.4 m deep (Figure 27). This removed at least 50 m^3 of sediment that was deposited as a convex plume further downstream, where the surface flow infiltrated into the alluvium. This resulted in 8.0 cm of aggradation at the third cross-section in this reach (C_P2.0c) (Figure 28), which was 30 m downstream of the deepest incision. At the time of the May 2005 survey, the convex depositional plume was slowly moving upstream as the deposited sediment reduced the channel gradient and hence the sediment transport capacity. The changes at cross-section C_P2.0b, which was between the incising and aggrading cross-sections, indicate that the incised channel extended downstream episodically during periods of higher flow (Figure 29). The convex deposit approximately 6.5 m from the left rebar probably formed during the initial episode of incision and extended across most of the channel. A second episode truncated this deposit and formed a new deposit approximately 8.5 m from the left rebar, adjacent to the low flow channel. This second deposit was mostly removed as the low flow channel extended downstream during subsequent episodes of incision. The next cross-section was about 20 m downstream, and the cross-sectional surveys indicated very little incision or aggradation during winter 2004–05.

Snowmelt and the runoff from the April storm also incised a similar low flow channel upstream of the second perennial storage reach, $C_P1.9$. This incision resulted in the deposition of a convex plume of sediment in the two upstream cross-sections of this reach, $C_P1.9a$ and $C_P1.9b$. After the initial deposition but prior to the May 2005 survey, a narrow channel incised through these new deposits as well as the former channel bed (Figure 30). This channel extended from $C_P1.9a$ downstream past $C_P1.9c$.

In the third storage reach, $C_P3.3$, the flood of 27 September 2004 had incised a low flow channel. Over the winter of 2004–05 there was 6.0 cm of incision, but this did not result in any deposition outside the low flow channel within the study reach or further downstream.

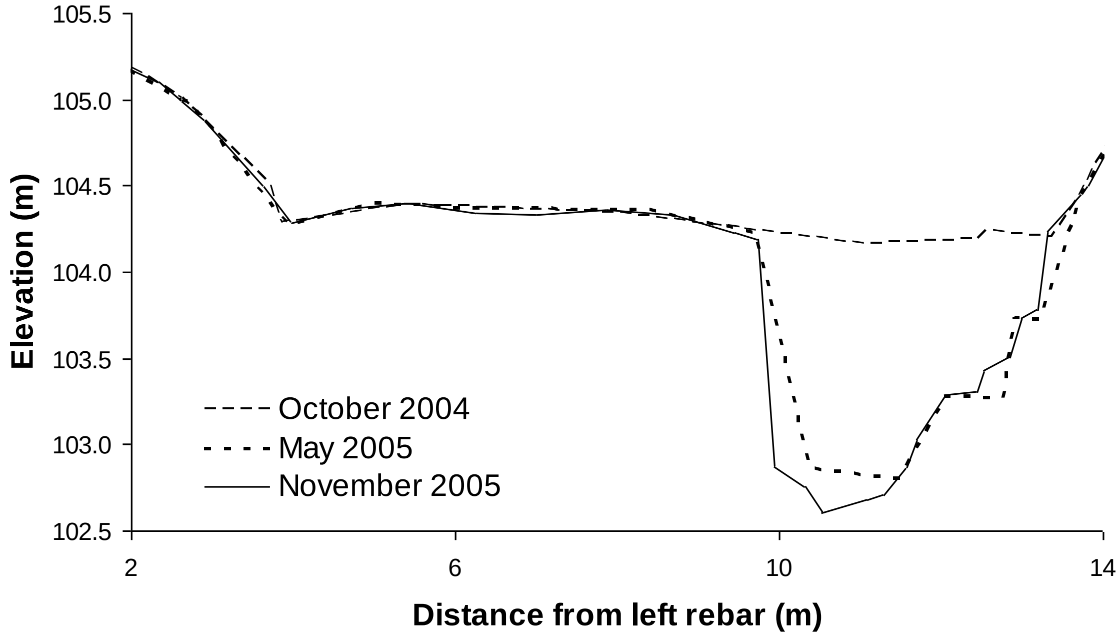


Figure 27. Changes in Saloon Gulch cross-section C_P2.0a from October 2004 to November 2005. The incision over winter 2004-05 caused the flow in this reach to shift from ephemeral to perennial.

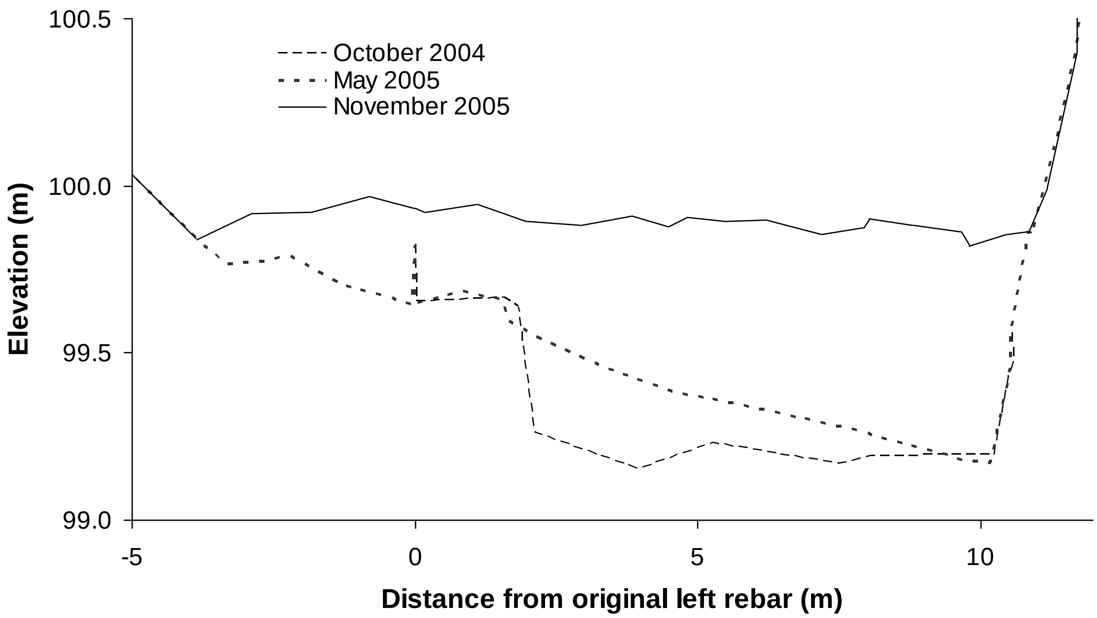


Figure 28. Aggradation in Saloon Gulch cross-section C_P2.0c over winter 2004-05 and summer 2005. The extensive changes necessitated moving the left endpoint of the cross-section.

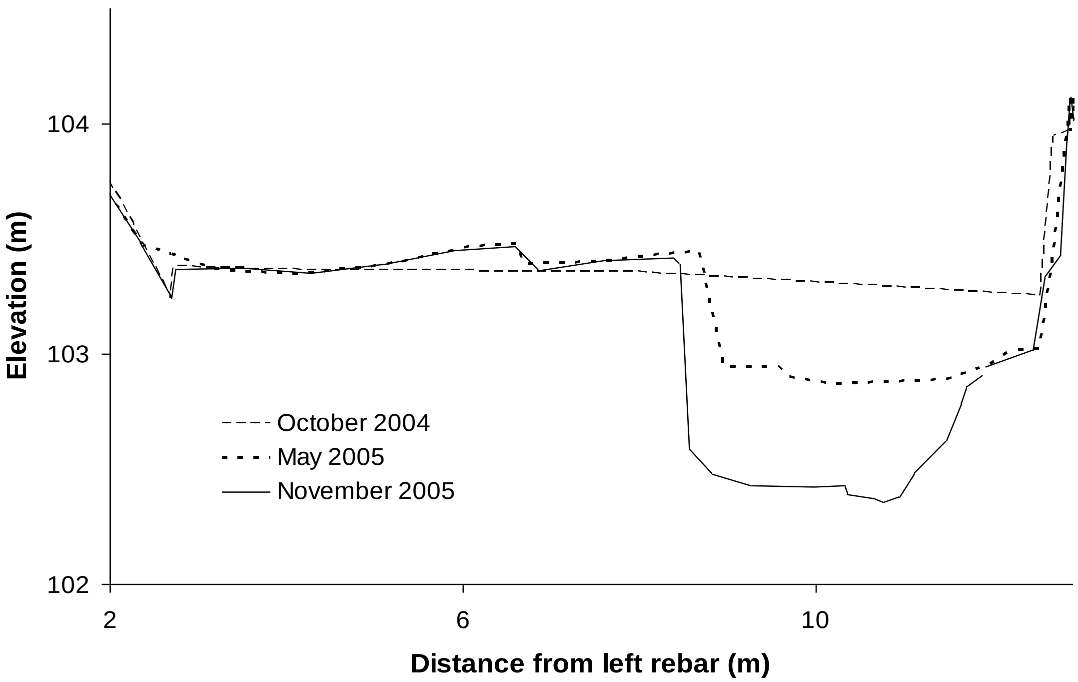


Figure 29. Incision in Saloon Gulch cross-section C_P2.0b over winter 2004-05 and summer 2005. The two deposits to the left of the incised channel at approximately 6.5 and 8.5 m indicate different episodes of incision and aggradation.

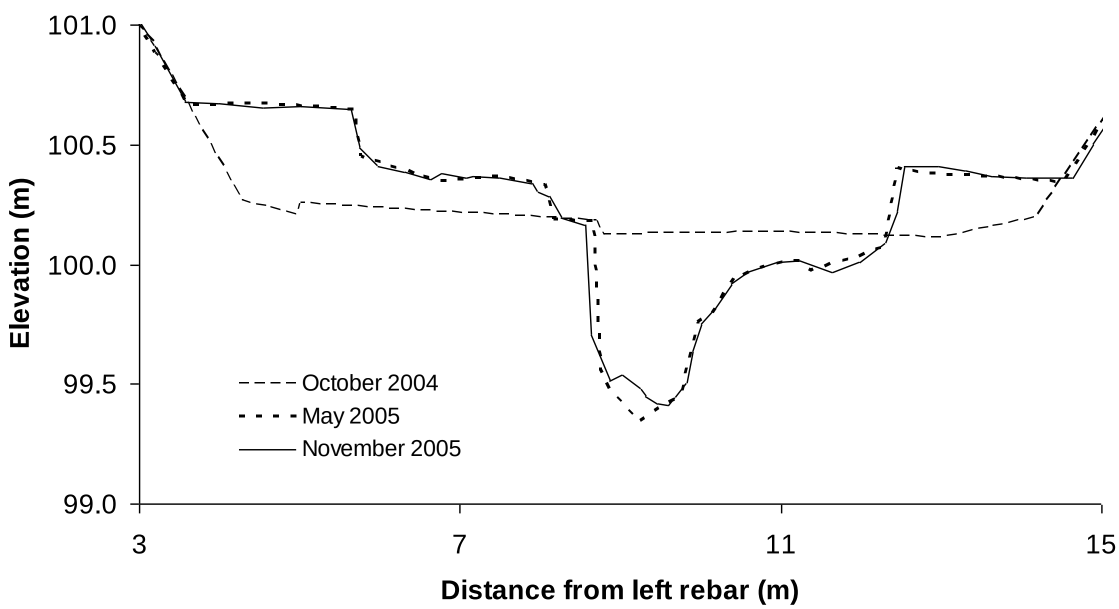


Figure 30. Aggradation followed by incision at cross-section Cp1.9a in Brush Creek.

4.3.3. Summer 2005

The absence of large storms in summer 2005 resulted in much less cross-sectional change except in the gully reaches (Figure 20). The mean ΔMBE in the rills was 0.0 cm (s.d.<0.1 cm), and the mean reach ΔMBE was never more than the 0.1 cm resolution of the surveys (Figure 31a; Table 10). There was no measurable change in 58 of the 63 cross-sections. Four cross-sections had a mean ΔMBE of -0.2 cm, whereas one cross-section aggraded 0.1 cm.

In summer 2005 net aggradation was observed in each of the six gully reaches, and the overall mean change was 1.5 cm (s.d.=1.5 cm) (Figure 20). In half of the reaches all of the cross-sections aggraded (Figure 31b; Table 10), and the spatial pattern of change indicated that most of this aggradation was due to bank collapse. The largest change was 5.9 cm in reach G5, and this was due to the deposition of material from a large bank collapse immediately upstream of cross-section G5c. The mean ΔMBE in the other five gullies was 0.9 cm (Figure 31b). The greater aggradation and bank collapse in the gullies relative to the rills was because the gullies were deeper and generally had steeper and less stable banks. This difference was clearer in summer 2005 than the other seasons because there was no surface flow to remove the deposits and transport the sediment further downstream. Reach ΔMBE was positively correlated with channel slope ($p=0.04$), but this relationship was not significant when the G5 reach was excluded and there is no apparent process-based explanation for the relationship. There was no significant correlation between ΔMBE and contributing area.

In the ephemeral channels the mean ΔMBE was 0.0 cm (s.d.=1.4 cm) (Figure 20). The crest gages indicated that there was no surface runoff in either the gullies or the

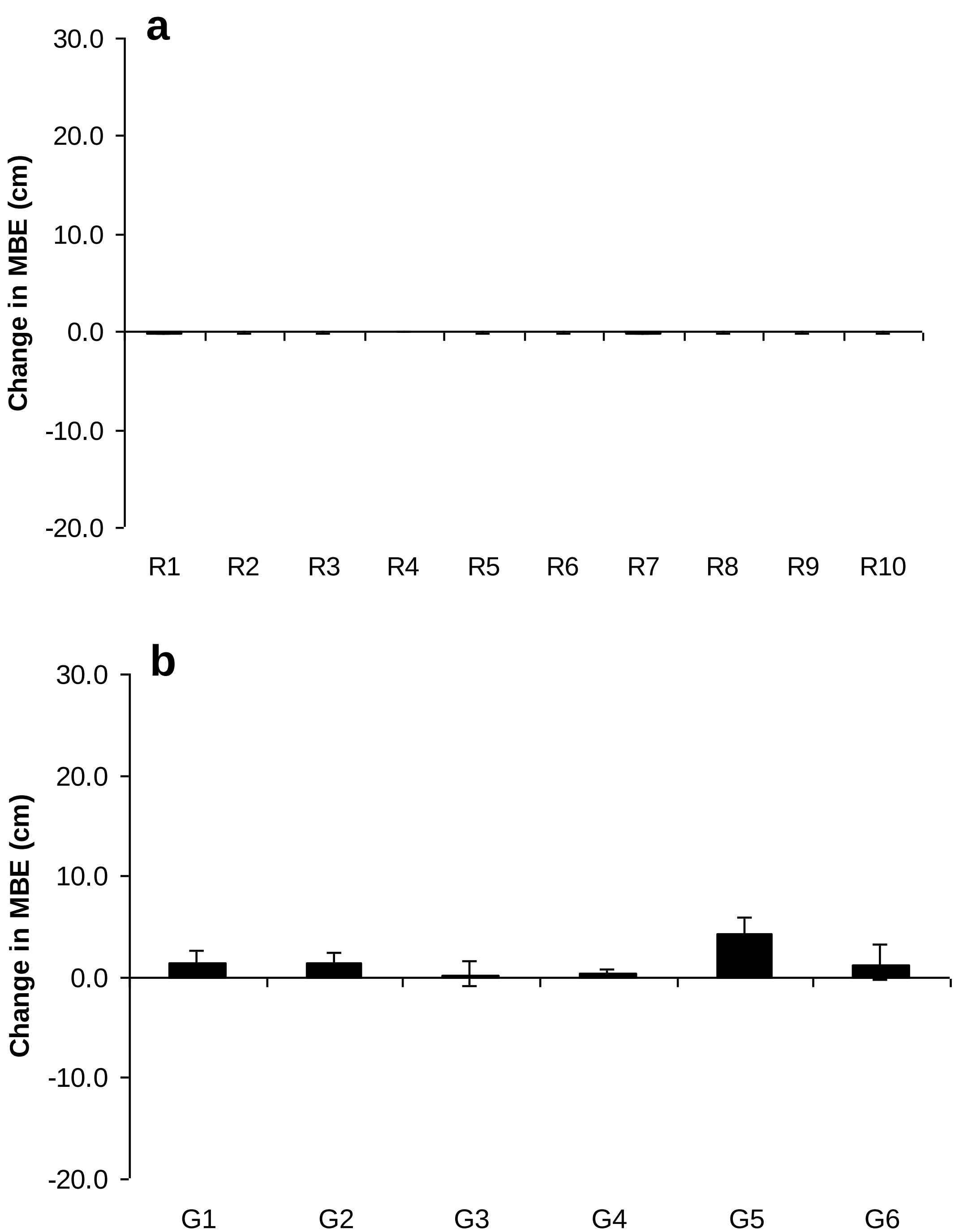
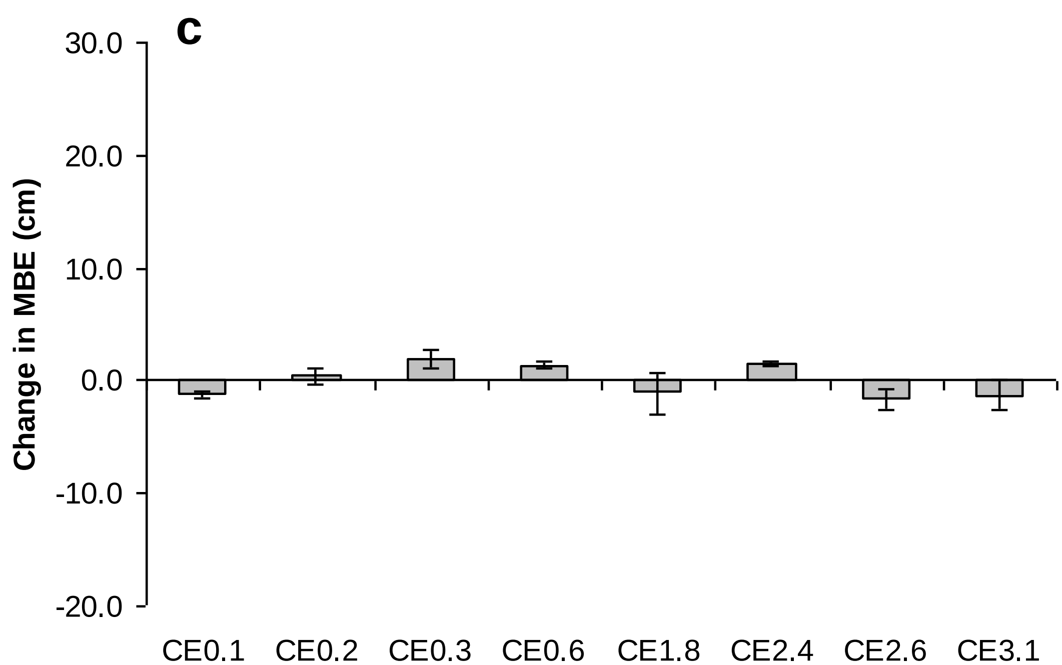
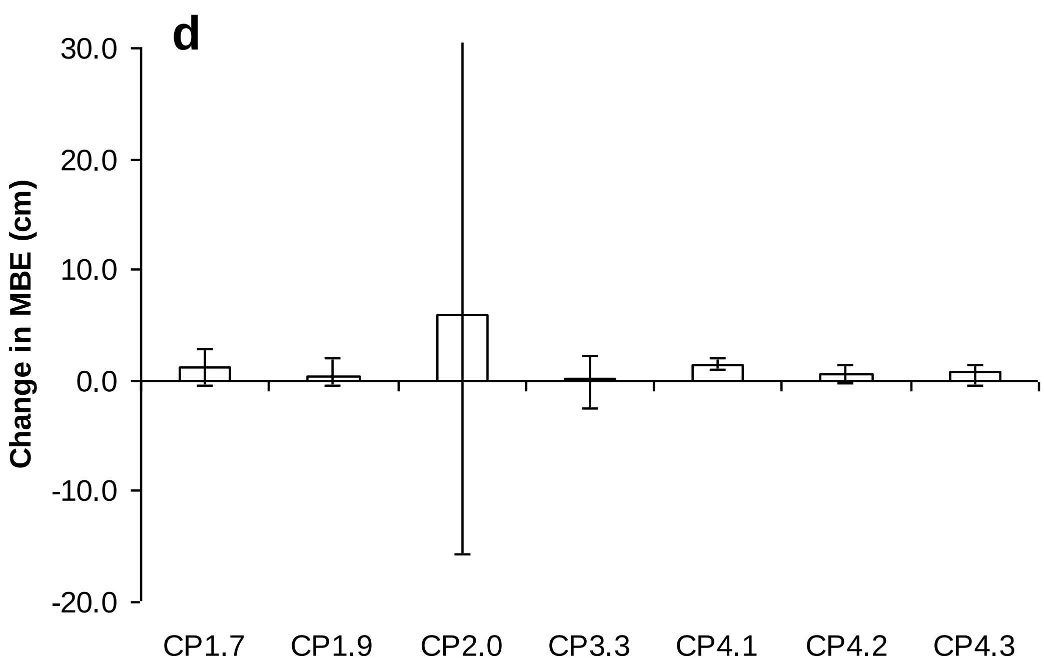


Figure 31. Change in mean bed elevation in summer 2005 for: (a) rill reaches; (b) gully reaches; (c) ephemeral channel reaches; and (d) perennial channel reaches. Bars represent minimum and maximum change at individual cross-sections.


c
30.0
20.0
10.0
0.0
-10.0
-20.0
Change in MBE (cm)
CE0.1
CE0.2
CE0.3
CE0.6
CE1.8
CE2.4
CE2.6
CE3.1


d
30.0
20.0
10.0
0.0
-10.0
-20.0
Change in MBE (cm)
CP1.7
CP1.9
CP2.0
CP3.3
CP4.1
CP4.2
CP4.3

ephemeral channels in summer 2005, and this means that there was no sediment delivered to the ephemeral channels or exported from Saloon Gulch. Bank collapse was observed in some reaches in Lower Saloon Gulch, but this localized aggradation was not large enough to affect the ΔMBE when averaged across the 12–54 m width of the active channels. Other than reach C_E2.0, which became perennial in the previous winter, the largest change was 1.9 cm in C_E0.3 (Figure 31c; Table 10); since no bank collapse was observed in this or the other reaches in Upper Saloon Gulch, this change has to be attributed to measurement error.

In the six perennial Brush Creek reaches the mean ΔMBE in summer 2005 was 0.8 cm (s.d.=0.4 cm) (Figure 31d; Table 10). This aggradation was due to bank collapse into the low flow channel, and to the downstream delivery and deposition of sediment by baseflows. In the four reaches in Lower Brush Creek there was 0.6 cm (s.d.=0.6 cm) of aggradation between May and July and only 0.3 cm (s.d.=0.4 cm) of aggradation from July to November. Although these measurements are less than the assumed minimum detectable ΔMBE of 1.0 cm, the aggradation is believed to be real since the ΔMBE values were consistent both between and within reaches and the aggradation within the low flow channel generally was greater than 1.0 cm. The greater aggradation during the first part of the summer also is consistent with the ability of the higher streamflows to deliver more sediment from the steeper reaches in the upper watershed and deposit it in the flatter study reaches in the lower watershed. There was no significant relationship between ΔMBE and contributing area or slope in the Brush Creek perennial reaches.The mean ΔMBE was 6.0 cm in the newly-perennial reach in Saloon Gulch (C_P2.0) (Figure 31c). This aggradation occurred in early summer due to the incision of a low flow channel and downstream deposition of the excavated sediment. This incision and downstream deposition meant that, in contrast to the perennial reaches in Brush Creek, change was extremely variable among the four cross-sections (Figure 31d). In the upper two cross-sections the thalweg of the low flow channel incised an additional 20–51 cm after the survey on 22 May (Figure 27; Figure 29). The excavated sediment accumulated in a convex deposit downstream that caused the thalweg of cross-section C_P2.0c to aggrade by 65 cm and the ΔMBE to increase by 40.5 cm (Figure 28). At the fourth and final cross-section the ΔMBE was comparatively small at 2.0 cm, as it was downstream of the convex deposit and the majority of surface flow infiltrated into the alluvium before reaching cross-section C_P2.0d. Hence little if any sediment was evacuated from this reach in summer 2005.

In July 2005 pebble counts were conducted in the low flow channel and the adjacent terrace at three cross-sections along reach C_P3.3 in Lower Brush Creek. This terrace was formed by the flood on 23 July 2004 and was not accessed by subsequent streamflows. The particle-size distribution in the low flow channel was significantly coarser than the surface of the terrace ($p<0.0001$), and the differences between the low flow channel and the terrace increased from approximately ¼ phi class for the D_{16} to about ½ phi class for the D_{50} and D_{84}, and more than one phi class for the D_{95} (Figure 32). These differences in particle size indicate that the 2004 floods had transported and deposited fine particles, but the subsequent snowmelt, stormflows and baseflows had resulted in a coarser particle-size distribution in the low flow channel.

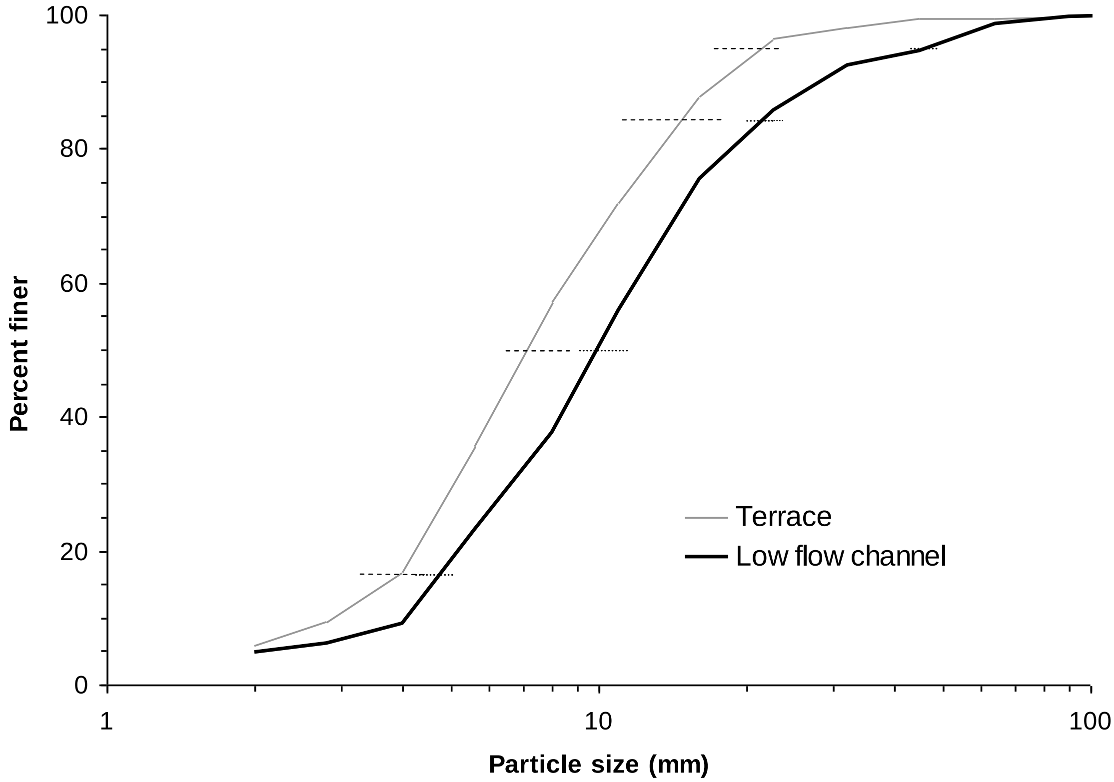


Figure 32. Mean particle-size distribution from pebble counts in the low flow channel in each of three cross-sections and the adjacent terrace in a perennial channel reach in Brush Creek in July 2005. Dotted lines indicate the range of particle sizes for the D_{16}, D_{50}, D_{84}, and D_{95} percentiles.

The pebble counts in July 2005 from the low flow channel in reach $C_P3.3$ showed no significant differences in the particle size distributions between the three cross-sections (Figure 33). The repeated pebble counts in November 2005 showed that the upstream cross-section ($C_P3.3b$) became coarser whereas the two lower cross-sections ($C_P3.3d$ and $C_P3.3e$) became finer (Figure 33). These changes meant that the bed surface in the low flow channel was significantly coarser in the upstream cross-section than the two downstream cross-sections ($p<0.0001$) in November. The upstream coarsening is attributed to the preferential entrainment and removal of the fine particles by summer baseflows, as the local channel slope was 5%. The fine particles eroded from the upstream cross-section were deposited in the downstream cross-sections, as the local channel slope was only 2%. These results help confirm that some bedload transport continued during summer baseflows.

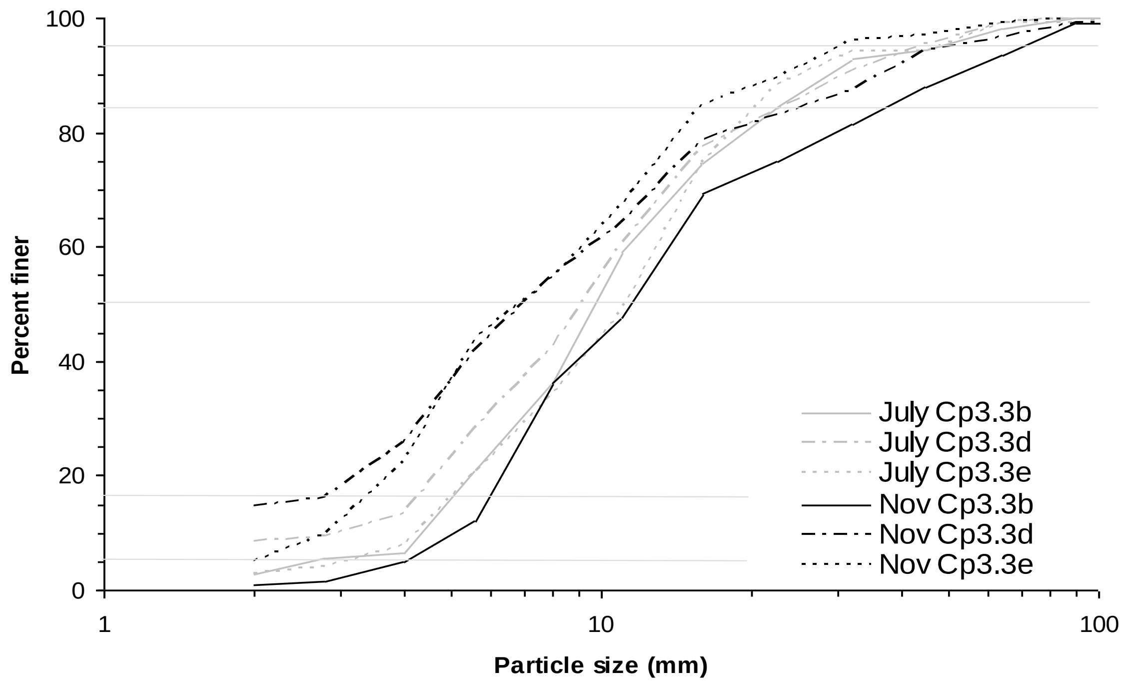


Figure 33. Particle-size distributions in July and November 2005 for three cross-sections in the low flow channel of perennial reach C_P3.3 in Lower Brush Creek. Letters b, d, and e indicate the order of cross-sections from upstream to downstream.

4.4. EMPIRICAL MODELS OF CHANGE IN MEAN BED ELEVATION

The values for the watershed- and reach-scale variables used in the development of the empirical models for reach-scale ΔMBE for floods, summer 2004, winter 2004-05, and summer 2005 are listed in Table 11. The best empirical model for reach-scale changes in mean bed elevation due to floods could only explain 25% of the observed changes (Table 12a). This model included the two categorical drainage type variables (gully and downstream ephemeral) and the continuous variables of maximum I_{30}, mean maximum I_{30}, antecedent moisture, depth, and slope*depth (Table 12a). The predicted ΔMBE values were very sensitive to the maximum I_{30} and mean maximum I_{30} (Table 12), but the correlations between I_{30} and the observed changes were weak, as indicated by the low model R^2. Antecedent moisture was included because drier conditions were strongly correlated with |ΔMBE| (Figure 18) and presumably the magnitude of runoff. The inclusion of channel depth and channel slope*depth was probably due to the very large changes in ΔMBE in the three storage reaches, as these were among the deepest and flattest reaches.

Reach ID	Contributing area (km^2)	Percent burned at high or moderate severity	Mean active width (m)	Mean depth (m)	Mean slope (%)	Mean width-to-depth ratio	Mean slope* depth (m)	Mean confinement
G1	0.003	100	0.7	0.39	14	3.6	0.06	1.00
G2	0.005	100	1.0	0.43	14	3.2	0.06	1.00
G3	0.024	100	1.6	0.45	11	3.8	0.05	1.00
G4	0.016	100	1.4	0.25	11	7.6	0.03	1.00
G5	0.017	99	1.3	0.33	21	3.7	0.07	1.00
G6	0.017	100	1.3	0.26	18	6.5	0.05	1.00
C_E0.1	0.003	100	7.6	0.23	16	32.5	0.04	1.00
C_E0.2	0.006	100	2.8	0.31	10	9.0	0.03	0.93
C_E0.3	0.063	100	1.3	0.34	9	6.8	0.03	0.98
C_E0.6	0.236	100	4.9	0.29	9	17.9	0.03	0.71
C_E1.8	2.193	74	19.9	0.58	10	34.2	0.06	0.44
C_E/C_P2.0	2.320	70	11.6	0.93	6	12.6	0.05	0.59
C_E2.4	2.437	63	53.9	1.11	8	48.3	0.09	0.52
C_E2.6	3.289	55	20.7	0.66	9	31.6	0.06	0.32
C_E3.1	3.424	53	18.2	1.01	10	18.0	0.10	0.18
C_P1.7	3.573	96	3.1	1.23	7	2.7	0.09	1.00
C_P1.9	3.612	96	13.7	1.52	7	9.1	0.11	0.55
C_P3.3	5.303	76	11.8	1.32	4	8.9	0.05	1.00
C_P4.1	5.930	67	2.0	1.13	6	3.8	0.07	0.58
C_P4.2	6.003	67	3.3	1.57	6	4.4	0.09	0.78
C_P4.3	6.045	66	8.0	1.23	4	9.2	0.05	1.00

Table 11. Values for the watershed-scale and reach-scale independent variables used in the empirical models of ΔMBE.

(a) Floods (n=76)

R^2 = 0.25; Adjusted R^2 = 0.16; RMSE = 0.040 m.

Variable	Parameter estimate	p-value
Intercept	-0.1160	0.0021
Gully	0.0733	0.0163
Ephemeral channel	0.0689	0.0052
Maximum I_{30} (mm hr^{-1})	**-0.0053**	**0.0057**
Mean maximum I_{30} (mm hr^{-1})	**0.0082**	**0.0011**
Antecedent moisture (mm)	0.0101	0.0617
Depth (m)	**0.1281**	**0.0006**
Slope*depth (m)	-0.0124	0.0028

(b) Summer 2004 (n=21)

R^2 = 0.72; Adjusted R^2 = 0.54; RMSE = 0.047 m.

Variable	Parameter estimate	p-value
Intercept	-1.0787	0.0031
Gully	-0.0387	0.6412
Ephemeral channel	-0.1181	0.1828
Mean total erosivity (MJ mm ha^{-1} hr^{-1})	0.0020	0.0033
Depth (m)	**0.6719**	**0.0008**
Slope (%)	0.0292	0.0100
Slope*depth (m)	**-0.0919**	**0.0010**
Confinement (m m^{-1})	-0.1734	0.0582

(c) Winter 2004-2005 (n=21)

R^2 = 0.59; Adjusted R^2 = 0.49; RMSE = 0.020 m.

Variable	Parameter estimate	p-value
Intercept	-0.2037	0.0089
Gully	0.0686	0.0114
Ephemeral channel	0.0828	0.0016
Contributing area (km^2)	0.0139	0.0472
Percent burned	0.0012	0.0369

(d) Summer 2005 (n=21)

R^2 = 0.81; Adjusted R^2 = 0.68; RMSE = 0.010 m.

Variable	Parameter estimate	p-value
Intercept	0.1646	0.0007
Gully	**-0.0851**	**0.0002**
Ephemeral channel	**-0.0720**	**0.0001**
Contributing area (km^2)	-0.0103	0.0269
Percent burned	-0.0007	0.0423
Width (m)	**0.0024**	**0.0056**
Depth (m)	-0.0511	0.0295
Slope (%)	0.0020	0.0667
Width:depth (m m^{-1})	**-0.0021**	**0.0051**

Table 12. Summary of the empirical models for estimating the reach-scale ΔMBE in meters for: (a) floods; (b) summer 2004; (c) winter 2004-05; and (d) summer 2005. Variables in bold have a substantially higher influence on model predictions than the other variables included in the model.

The summer 2004 model had a much higher R2 of 0.72, and this is partly due to the smaller number of data points to fit and the wider range of ΔMBE values (Table 12b). The variables included in this model were the same two drainage type variables, one precipitation variable (mean total erosivity), and four reach-scale variables: mean total erosivity, channel depth, channel slope, slope*depth and confinement. The inclusion of the four reach-scale variables is difficult to interpret. The use of seven variables to predict ΔMBE for 21 reaches suggests that the model may be over-parameterized, even though the adjusted R2 was 0.54 and the model selection process means that each variable appreciably improved the model fit. Because the reach-scale variables were the only variables that could differ greatly between nearby reaches, they were the only variables that could be used to predict the large differences in ΔMBE between nearby reaches.

The drainage type variables were included because they were intrinsic to the study goals, but they were not statistically significant in the summer 2004 model. The lack of significance is probably because drainage type was confounded by the reach-scale variables. In particular the gullies were generally shallower, steeper, more confined, and had lower slope*depth values than perennial channels; the ephemeral channels generally were shallower, less confined, and had lower slope*depth values than the perennial channels. Because much of the variability in ΔMBE between the drainage types was explained by the reach-scale variables, drainage type was not significant.

The winter 2004–05 model had an R^2 of 0.59, and this used the two categorical drainage type variables and two continuous watershed-scale variables, contributing area and percent burned (Table 12c). The significance of drainage type is probably due to the fact that the gullies and ephemeral channels had much less winter incision than the perennial channels. The inclusion of contributing area and percent burned indicates that the position of the reach within the watershed was an important determinant of ΔMBE. In winter 2004–05 the greatest ΔMBE was the incision in the perennial reaches, and these reaches had the largest contributing areas. The absence of any reach-scale variables is attributed to the more spatially consistent ΔMBE among reaches of the same drainage type in winter 2004-05 as compared to summer floods (Figure 20).

The model for summer 2005 had the highest R^2 of 0.81, and this model included the two drainage type variables as well as contributing area, percent burned, active channel width, channel depth, channel slope, and width-to-depth ratio (Table 12). The strong influence of drainage type in this model (Table 12d) underscores the importance of perennial flow as a driver of channel change during the drier summer of 2005. The exclusion of precipitation variables from the model is attributed to the absence of floods in summer 2005. The inclusion of contributing area and percent burned may be due to the weak but non-significant inverse relationships between contributing area and ΔMBE for ephemeral channels (R^2=0.26) and perennial channels (R^2=0.45). There is no physical basis for either of these relationships, since much of the ΔMBE in the ephemeral channels may have been measurement error, and the relationship in the perennial channels were strongly influenced by the large amount of aggradation in reach C_P2.0 in Saloon Gulch, as this reach had one of the smallest contributing areas. The inclusion of the four reach-scale variables can be attributed to their ability to help explain the high variability among nearby ephemeral reaches.

5. DISCUSSION

5.1. ACCURACY AND VARIABILITY OF CHANGE IN MEAN BED ELEVATION

The accuracy of the total station cross-section measurements can be assessed from the measured ΔMBE in the ephemeral channel cross-sections when there was no surface flow or obvious bank collapse. During these periods most of the measured change can be attributed to measurement error, because other factors such as freeze-thaw were minor or not documented by the more accurate pin-frame measurements in the rills (Piestraszek, 2006). In winter 2004–05 there were 15 cross-sections in five ephemeral channel reaches that had no evidence of surface flow or bank collapse, and the mean seasonal |ΔMBE| in these cross-sections was 0.9 cm (s.d.=0.4 cm). Within the reaches the positive and negative cross-section errors largely offset each other, so the mean reach-scale |ΔMBE| was only 0.2 cm (s.d.=0.1 cm). Averaging the ΔMBE from the five reaches further reduced the overall mean |ΔMBE| to 0.1 cm. The progressive reduction in |ΔMBE| indicates that most, if not all, of the ΔMBE in these 15 reaches was due to random surveying errors.

In summer 2005 there were 25 cross-sections in eight ephemeral channel reaches that also should have had no change in ΔMBE due to the lack of surface flow and bank collapse. The mean |ΔMBE| among these cross-sections was 1.4 cm (s.d.=0.4 cm), but in this case the cross-section ΔMBE values did not offset each other within each reach, as the mean reach |ΔMBE| was 1.3 cm (s.d.=0.4 cm). The reach errors did offset each other when averaging among the reaches, as the overall average ΔMBE was 0.0 cm.

The May and November 2005 surveys were more precise and detailed than the October 2004 survey, so the ΔMBE values for the 25 cross-sections that should have shown no change were more consistent. The mean standard deviation of ΔMBE for the cross-sections within the eight reaches was 0.8 cm for summer 2005, but in six of these reaches the measured incision or aggradation exceeded 1.0 cm. The cross-section ΔMBE values were more tightly clustered in summer 2005, and this suggests that the height of the total station was measured less accurately for this period even though the same procedure was carefully followed for each survey.

This analysis indicates that cross-section ΔMBE values larger than approximately 1.8 cm (the mean error for summer 2005 plus one standard deviation) probably represent “true” incision or aggradation in the gullies and channels. The sources of error appear to be random and at least partially offsetting when the cross-sections are pooled by reach, so reach ΔMBE was probably accurate to within 0.3 cm (winter 2004–05) or 1.7 cm (summer 2005). Pooling the reaches by drainage type further reduces the effect of random errors, so the mean ΔMBE by drainage type is probably accurate to within 0.2 cm. The accuracy of the individual cross-section measurements is higher in the rills because a rigid pin frame was set onto fixed endpoints. For the rills the ΔMBE at individual cross-sections is probably accurate to within 0.1 cm, and the reach error is probably even less.

The much larger changes in ΔMBE in summer 2004 mean that the measurement errors are proportionally less important. The large changes in ΔMBE between surveys mean that the accuracy in summer 2004 is more difficult to determine, but the accuracy should not be substantially different than the estimated reach-scale accuracy from summer 2005.

5.2. PHASE I CHANGES IN THE DRAINAGE NETWORK

The channel change measured in summer 2004 is consistent with the expected Phase I response to fire, as there was storm-driven erosion in the uppermost portions of the drainage network and net deposition in the lower gradient reaches further downstream (Table 13) (Helvey, 1980; Laird and Harvey, 1986; Florsheim et al., 1991; Minshall et al., 1998; Moody and Martin, 2001b). This response is primarily due to elevated storm runoff, which in this area persists for 3–4 years after a high severity burn (Moody and Martin, 2001b), and to hillslope erosion, which is greatest when percent bare soil is greater than approximately 60% (Pietraszek, 2006). In summer 2002 and 2003, the mean percent bare soil on the severely burned hillslopes was 94% and 84% respectively (Rough, 2007). Sediment production normalized by total rainfall erosivity was 0.032 Mg hr MJ^{-1} mm^{-1} in each of the first two summers after burning (Figure 34) (J. Pietraszek, unpublished data). Summer 2004 was a transitional season in which the proportion of bare soil was reduced to 55%, and the normalized rate of sediment production declined by about half to 0.015 Mg hr MJ^{-1} mm^{-1} (Figure 34).

Phase I concludes when the hillslope runoff and erosion rates decline to near-background levels, and moderate summer storms no longer cause floods in the gullies and ephemeral channels. A compilation of data from 10 fires in the Colorado Front Range shows that hillslope erosion rates are very low when there is less than 40% bare soil (Pietraszek, 2006). In summer 2005 and 2006, normalized sediment production was only 2–4% of the initial rate (Figure 34) (K. Schaffrath, unpublished data). A precise

Recovery Period		State of Hillslopes, Vegetation, and Runoff	Rills and Gullies	Ephemeral Channels	Perennial Channels
Phase I Initial response to high-severity wildfire	**Summer**	Overland flow and high sediment production during 8-10 mm hr^{-1} storms. Hillslopes >40% bare soil.	Incision due to increased overland flow and absence of stabilizing vegetation.	Aggradation concentrated in lower gradient reaches.	Aggradation concentrated in lower gradient reaches.
	Winter/ Snowmelt	Snowpack potentially larger due to reduced interception. Melt accelerated due to increased solar radiation and turbulent heat transfer.	Slight aggradation due to bank collapse and freeze/thaw. Incision possible in gullies during large frontal rainstorms.	No change in most reaches. Localized small-scale incision due to rivulets in a few reaches.	Widespread incision through post-fire deposits in the low-flow channel.
Phase II Recovery trajectory due to initial vegetative regrowth and decreased runoff and erosion rates	**Summer**	Infiltration rates approach pre-fire levels, so overland flow is rare. Increased vegetation on hillslopes and in riparian areas, but no mature forest. Hillslopes <40% bare soil.	No incision due to absence of flow and presence of stabilizing vegetation. Minor aggradation due to soil diffusion from the hillslopes or bank collapse.	Little change since flow is sub-surface, except in extreme storms. Banks collapse and sediment may be slowly redistributed across the channel.	In-channel aggradation abates as upstream channels become stabilized by vegetation. Incision if baseflows and stormflows can transport the available sediment.
	Winter/ Snowmelt	Similar to Phase I, since initial vegetation would intercept little snowfall and provide little shade during snowmelt.	Aggradation due to bank collapse and freeze/thaw. Incision unlikely, even during large storms, due to increased depth of colluvium and stabilizing vegetation.	Little change likely. Banks collapse and sediment may be slowly redistributed across the channel. Flow is primarily subsurface, and micro-incision abates due to stabilizing vegetation in channel.	Incision slowly moderates as the bed becomes coarser, and bedforms increase surface roughness.
Phase III Background sediment transport rates in perennial channels	**Summer**	Overland flow extremely rare. Hillslopes re-vegetated and mostly covered by vegetation and litter (<10-15% bare soil).	Slow colluvial aggradation as cross-sectional profile becomes smooth, banks are no longer well-defined and erodible, and vegetation and litter limit soil movement. Drainages indistinct from hillslopes.	No change since flow is sub-surface except in extreme storms, and valley is vegetated.	Baseflows and storm quickflows cause little change because the bed material is as coarse as before the fire and banks are vegetated.
	Winter/ Snowmelt	Snowpack and spring runoff return to pre-fire conditions with development of forest canopy.	Slow colluvial aggradation as cross-sectional profile becomes smooth, banks are no longer well-defined and erodible, and snow, vegetation and litter limit soil movement. Drainages indistinct from hillslopes.	No net change due to lower flows, stabilizing vegetation, and litter.	Little change since sediment supply has declined, the bed material is as coarse as before the fire, the banks are vegetated, and snowmelt runoff has returned to pre-fire levels.
Long- term Implications		Mature forest and riparian communities; surface flow only during the most extreme summer rainstorms	Hillslope swales slightly deeper than before the fire.	No defined channel; alluvium incrementally deeper than before the fire.	Post-fire sediment evacuated from the low-flow channel but stored in discontinuous terraces.

Table 13. Observed and predicted trajectory of change in swale axis rills, gullies, ephemeral channels, and perennial channels following a high severity wildfire in the Colorado Front Range.

determination of hillslope and watershed-scale recovery is difficult because the largest storm in Saloon Gulch in summer 2005 had a mean maximum I_{30} of only 8 mm hr^{-1}. By summer 2006 the hillslopes had largely recovered, as summer storms with a mean maximum I_{30} of up to 24 mm hr^{-1} caused the highest total summer erosivity since the fire, but sediment production remained low and there were no floods (K. Schaffrath, unpublished data). The low sediment production and lack of floods in summer 2005 indicate that Phase I had ended, even though the hillslopes still averaged 42% bare soil (K. Schaffrath, unpublished data).

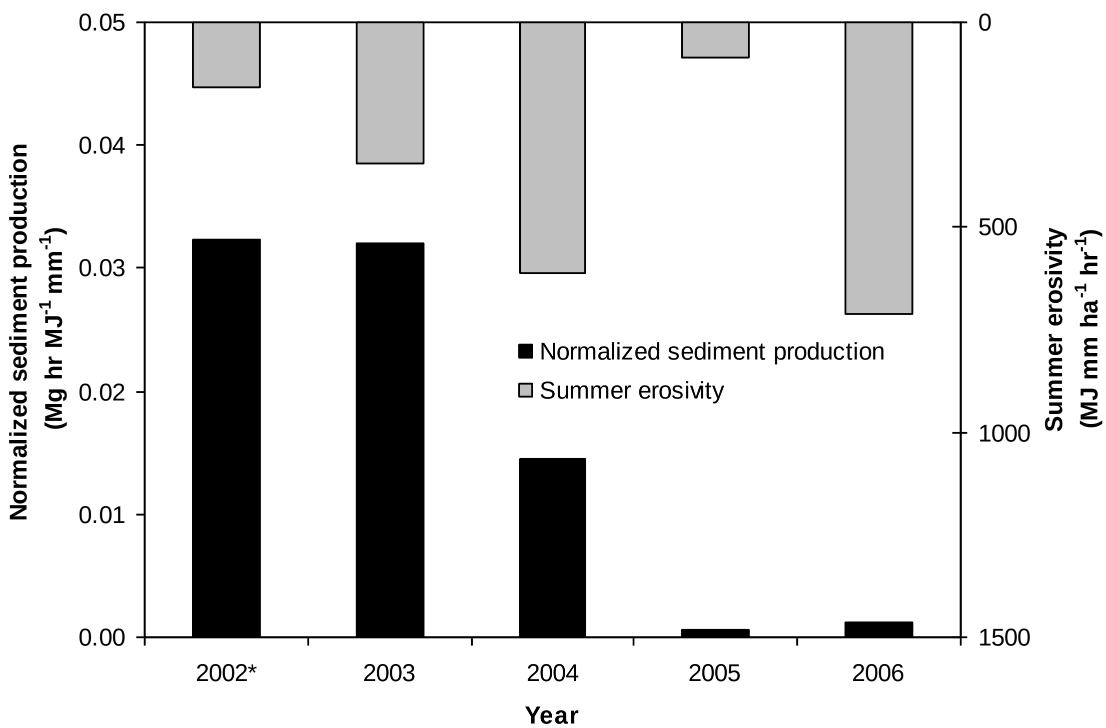


Figure 34. Hillslope-scale sediment yields in Upper Saloon Gulch normalized by summer erosivity, 2002-2006. * indicates that sediment measurements in 2002 only began in July.

The high post-fire erosion rates for the Hayman wildfire persisted longer than most other recent wildfires in the Colorado Front Range. Data from five other wildfires show that sediment production commonly declines by an order of magnitude between the second and third year after burning (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006), whereas in Saloon Gulch, the normalized erosion rate in the third summer after burning was still nearly 50% of the initial rate. The comparatively long recovery period can be attributed to the coarse soils that retain little water for vegetative re-growth (Pietraszek, 2006).

During Phase I, soil water repellency appears to influence the rate of runoff from moderate-sized storms and therefore the magnitude of flooding. Antecedent moisture was inversely related to $|\Delta MBE|$ (R^2=0.79; p=0.04) for the five floods in Saloon Gulch in summer 2004. Since soils that are not water repellent generally have higher infiltration rates when dry, this inverse relationship suggests that water repellency may still be increasing runoff. Data from Saloon Gulch shows a consistent decline in post-fire soil water repellency from 2002 to 2004, but soil water repellency at depths of 3 and 6 cm was still generally greater in the burned areas in summer 2004 than comparable unburned sites, although these differences were not statistically significant (Rough, 2007). These results suggest that soil water repellency was an important control on flood magnitude in summer 2004, and help explain why Phase I continued through summer 2004.

Point and small plot studies show that water-repellent soils become wettable when a minimum soil moisture threshold is reached (e.g., Doerr and Thomas, 2000; Doerr et al., 2003; MacDonald and Huffmann, 2004), but few studies have examined the effects of soil moisture on soil water repellency and runoff at the watershed scale (Doerr and

Moody, 2004). At larger scales, the effect of soil water repellency on infiltration and runoff is increasingly complicated by the patchiness of soil water repellency (Doerr and Moody, 2004; Woods et al., 2007), soil moisture (Rodriguez-Iturbe et al., 1995), and macropores (Doerr et al., 2003). If the soils are water repellent, an increase in antecedent moisture should reduce runoff, but the extreme patchiness in precipitation, soil moisture, and soil water repellency means that the threshold effect of soil moisture on soil water repellency could change to a more linear relationship between soil moisture and runoff at the watershed scale.

While antecedent moisture was significantly related to ΔMBE, there was not a significant relationship between |ΔMBE| and mean maximum I_{30} or maximum I_{30} (p=0.9). Most other studies have shown that rainfall intensity is the primary control on flood magnitudes and hillslope erosion after burning (Moody and Martin, 2001a; Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). The absence of a significant relationship in this study can be attributed to the extreme spatial variability in precipitation and the resulting variability in runoff and sediment inputs to the different reaches, the variability due to knickpoint incision and retreat, and the fact that |ΔMBE| is only a rough index of flood magnitude.

5.2.1. Drainage Formation and Upslope Channel Head Migration

The differences in channel head location and morphology between unburned and burned watersheds suggest fundamental differences in the processes by which channel heads are formed. The channel heads in the unburned watersheds are most likely formed by exfiltrating subsurface flow, because the well-vegetated 10–20 cm steps had seepage flow but no plunge pools (Dietrich and Dunne, 1993). In the burned areas the channel heads were gradual and there were no pronounced steps; this morphology is characteristic of channel heads formed by Horton overland flow (Dietrich and Dunne, 1993). The availability of pre- and post-fire data on hillslope-scale erosion and the expansion of the drainage network confirm that the dominant runoff process shifted from subsurface storm flow to Horton overland flow (Libohova, 2004; Pietraszek, 2006).

The generation of Horton overland flow from storms with an I_{30} of 8–10 mm hr^{-1} and the decrease in flow resistance causes the formation of a new channel network on the hillslopes and in zero-order basins (Moody and Martin, 2001b; Istanbulluoglu et al., 2004; Moody and Kinner, 2006; Pietraszek, 2006). Field observations show that the drainage network and channel head locations are established during the first significant storm. In Saloon Gulch and Brush Creek channel heads formed in the swale axes 10–30 m below the ridgetop in response to a 22 mm hr^{-1} storm with a 1-year recurrence interval (Pietraszek, 2006). In the case of the nearby Buffalo Creek fire, channel heads formed on planar hillslopes within 5 m of the ridgetop in response to a 90 mm hr^{-1} storm with a 100-year recurrence interval (Moody and Martin, 2001a; Moody and Martin, 2001b). The actual difference in the contributing areas for the channel heads between this study and Buffalo Creek is probably larger than the difference in the distance between the ridgetop and the channel head, as the channel heads in this study were in convergent areas as compared to planar hillslopes in Buffalo Creek. The smaller contributing areas for the channel heads after the Buffalo Creek fire is attributed to the much greater intensity of the initial storm after burning. In both the Hayman and Buffalo Creek fires there was relatively little change in the location of the channel heads and the density of the drainage network after the initial causative storm (J. Pietraszek, Colorado State University, pers.

comm., 2005; Moody and Kinner, 2006). The very small contributing areas in the burned watersheds relative to the unburned watersheds emphasizes the sharp change in runoff processes due to a high severity fire.

In humid and semi-arid unburned areas the contributing area for channel heads is inversely related to slope (Dietrich and Dunne, 1993). In this study, there was no correlation between contributing area and slope for the channel heads in the burned areas. For 8 of the 14 channel heads in the burned area the swale axis above the channel head was less steep than the gradient below the channel head. This indicates that these channel heads were upslope of the inflection point where the longitudinal profile shifts from convex to concave. Above this inflection point slope and drainage area both increase in the downstream direction, whereas below the inflection point channel slope decreases with increasing drainage area. Since nearly equal numbers of channel heads were located above and below the inflection point, there was not a consistent relationship between contributing area and slope. The fact that some channels extended upslope beyond the inflection point, despite decreasing slope, indicates that contributing area is more important than slope as a control on channel head location in severely burned areas. This result is consistent with Horton overland flow as the primary driver of drainage network extension after a high severity fire.

5.2.2. Rill and Gully Incision and Channel Aggradation

The hillslope and drainage network response to a high severity wildfire can be divided into three phases, and these are summarized in Table 13. Figure 35 shows the expected change in mean bed elevation over time for each drainage type. Rills and gullies are distinguished from downstream channels by their tendency to incise during Phase I

(Table 13; Figure 35). This initial response is most consistent higher up in the watershed, and in the first three years after burning each of the rill reaches incised during each summer storm (Pietraszek, unpublished data). During Phase I the gully reaches also generally incised, but the largest and most erosive storm on 14 July 2004 caused an average aggradation of 1.8 cm (Figure 21b). The gully reaches generally were within 100 m of the gully-channel transition points, and their response to the 14 July flood suggests that aggradation may begin higher in the drainage network during intense storms. Although there is a lack of hillslope erosion data from storms with a recurrence interval larger than two years, the available data do suggest a non-linear increase in sediment production with storm intensity (Pietraszek, 2006), and the proportionally greater increase in sediment yields relative to runoff would shift the upstream boundary of deposition further upslope. Although the upstream boundary of deposition did shift on a storm-by-storm basis, the gully-channel transition points did not change between early September 2004 and November 2005 because they were governed by the decrease in channel slope.

The ephemeral channel reaches both incised and aggraded in summer 2004, but deposition predominated as the floods washed sediment into these channels and redistributed it among the reaches (Table 13; Figure 35). Only three of the nine ephemeral channel reaches aggraded in summer 2004, but the magnitude of aggradation in one reach was so large that the mean response in the ephemeral channels was aggradation. The low proportion of aggrading reaches in summer 2004 can be attributed to the decline in runoff and sediment production rate at the hillslope scale. Field observations showed that the post-fire alluvium was at least 20 cm deep in each of the ephemeral study reaches, indicating that aggradation was the dominant process throughout the ephemeral channels during Phase I (Table 13; Figure 35).

The perennial channel reaches both incised and aggraded in summer 2004, but the overall response was aggradation (Table 13; Figure 35). On a seasonal basis, the sediment deposition during floods was partially counter-balanced by incision during snowmelt runoff and low-intensity spring rainstorms. This means that the net aggradation in the perennial channels from early summer 2004 to May 2005 was somewhat smaller than in the ephemeral channels (Figure 20), and this difference is probably typical of Phase I (Figure 35).

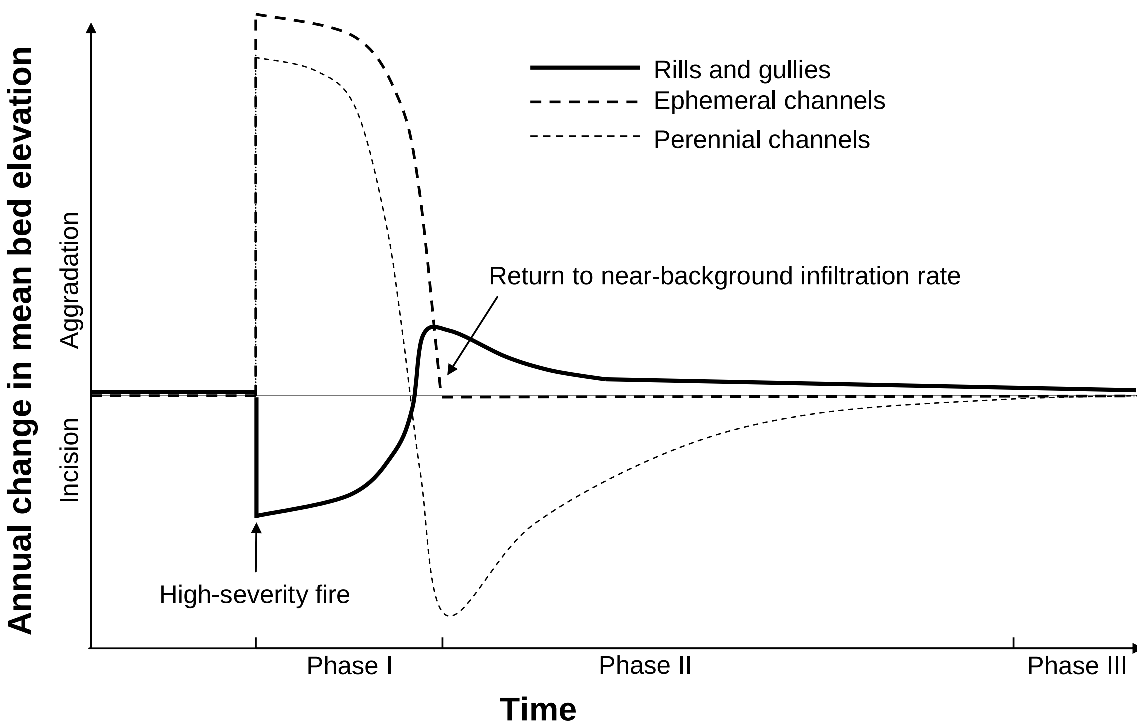


Figure 35. Schematic of annual change in mean bed elevation in rills and gullies, ephemeral channels, and perennial channels following a high severity fire. Axes not to scale.

Because aggradation in the three storage reaches controlled the mean direction of change in the ephemeral and perennial channels in summer 2004, it is important to evaluate whether the proportion of storage reaches in the study was representative of the burned watersheds. The storage reaches were unique in having a low flow channel with near-vertical banks incised into planar post-fire deposits and eroding pre-fire banks on both sides (Figure 36). In summer 2004 storage reaches represented 11% of the ephemeral channel study reaches and 33% of the perennial channel study reaches. The channel inventory in summer 2005 showed that this unique morphology was present in 14% of the 25 km of ephemeral and perennial channels in the two burned watersheds. These data indicate that the proportion of ephemeral storage reaches included in the cross-sectional monitoring was reasonably representative, whereas the perennial storage reaches were over-sampled relative to their frequency. Therefore the ΔMBE in the perennial channels in summer 2004 may be somewhat higher than the mean aggradation for all the perennial channels in the burned watersheds.

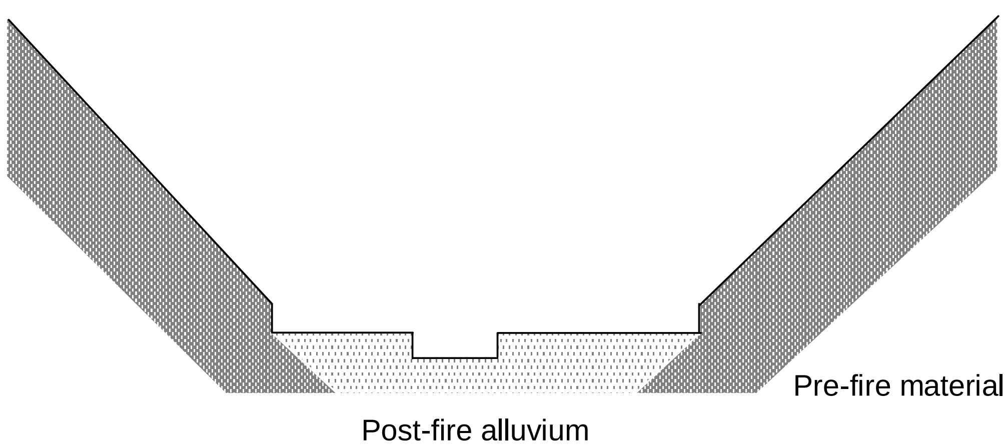


Figure 36. Unique morphological signature of the three storage reaches in the burned watersheds.

The net ΔMBE for the perennial channels during Phase I can be estimated by combining the ΔMBE data from 2002, 2004, and 2005 with the hillslope sediment production data from 2002 through 2004. For summer 2003 the ΔMBE was estimated by applying the ratio of hillslope sediment production to ΔMBE, as determined for summer 2004, to the sediment production data from summer 2003. This calculation yields about 5 cm of aggradation. The ΔMBE for summer 2002 was estimated by doubling the estimated ΔMBE for summer 2003, since the 2002 cross-section data show that channel aggradation from the initial storms was much greater than the aggradation from later storms; this assumption is quite conservative since the cross-sectional area of deposition was more than five times larger in summer 2002 than 2003 at the only cross-section (C_E2.0D) with data from immediately before and after the Hayman fire (Libohova, 2004). The ΔMBE during winter 2004–05 was approximately -5 cm, but spring runoff was 220% of normal so a better estimate of incision for the winters of 2002–03 and 2003–04 would be about half of this value. On this basis the total summer aggradation in the perennial channels during Phase I is estimated to be approximately 20 cm, and the total winter incision is estimated to be about 10 cm. Combining these estimates results in an overall aggradation of about 10 cm from summer 2002 to May 2005

5.3. PHASE II CHANGES IN THE DRAINAGE NETWORK

Phase II is defined as the recovery trajectory, when hillslope runoff and erosion is greatly reduced, colluvial processes cause the rills and gullies to aggrade on an annual basis, and snowmelt runoff and baseflows progressively evacuate the post-fire sediment from the perennial channels. On this basis Phase II began in summer 2005. Phase II was confirmed in summer 2006, as the highest summer erosivity since the Hayman fire caused very little hillslope runoff and erosion, and no floods in the ephemeral channels. As the hillslopes revegetate and the soil water repellency returns to pre-fire levels, hillslope runoff and floods will be progressively more unlikely in Saloon Gulch and Brush Creek because the permeability of the dominant soil series under unburned conditions is 150–510 mm hr^{-1} (Moore, 1992), which is much greater than the estimated intensity of the 100-year, 30-minute storm (D. Hall, USDA Forest Service Rocky Mountain Research Station, pers. comm., 2004).

Between October 2004 and November 2005 there were no floods, so the changes in mean bed elevation and the channel bed material over this period represent a complete year of the Phase II response. This means that the changes measured in this study can be used to estimate the time needed for the different drainage types to recover to pre-fire conditions.

From October 2004 to November 2005 the mean change in the rills was slight aggradation, which was primarily due to bank collapse in a small proportion of the cross-sections, and the lack of any surface runoff to remove these deposits or induce further incision (Table 13; Figure 35). A series of other processes can cause rills to aggrade and refill, and these include dry ravel enhanced by bioturbation (Booker et al., 1993), freeze-thaw, and alluvial deposition (Moody and Martin, 2001b). The mean rate of summer incision in the first three years was 30 times the rate of winter aggradation (Pietraszek, 2006). In theory this means that a century of aggradation would be necessary to fill in the rills that developed during the first three summers after burning. However, the aggradation rate should slow considerably once the banks collapse, and the increase in vegetation and organic litter slow dry ravel (Figure 35). As a rough prediction, the cross-sectional profile of the swales should become smooth within about fifty years, but slow colluvial infilling is likely to continue for a much longer period (Table 13).

The gullies also aggraded slightly from October 2004 to November 2005 because the 1.4 cm of incision during the winter was counteracted by 1.5 cm of summer aggradation. Aggradation is probably more typical in winter because freeze-thaw can cause banks to collapse (Table 13) (Moody and Martin, 2001b), but the incision in winter 2004–05 probably was caused by the 26 mm of rainfall in an April storm when the soils were already relatively wet from snowmelt and rainfall the previous day. The survey and crest gage data indicate that the runoff from this storm was mostly subsurface at the rill scale, but became surface runoff in many of the gullies. During summer 2005 more aggradation was observed in the gullies than the rills because the gullies had higher and less stable banks, and this comparatively rapid aggradation should continue for the first decade or so of Phase II (Figure 35). Within a decade of the fire, vegetative regrowth should stabilize the bed and banks (Moody and Martin, 2001b), and once this happens there should be little or no incision even if snowmelt and spring storms cause surface flow (Table 13). The gullies will require longer to refill than the rills because they are generally wider and deeper. After the nearby Buffalo Creek fire, Moody and Martin (2001b) hypothesized that gullies might require a millennium or longer to completely refill, based on the age of colluvium in unburned swales. As a rough prediction, the cross-sectional profile of the gullies should again become smooth within about one hundred years, but complete refilling will take much longer.

During Phase II, surface runoff from summer storms is extremely unlikely in the ephemeral channels. The bed of the ephemeral channels consists of deep, highly permeable alluvium, and any runoff from the hillslopes would quickly infiltrate and remain as subsurface flows (Table 13) except when there are exceptionally high volumes of rainfall or snowmelt. The observations from winter 2004–05, when the snowpack was much larger than average, indicate that surface flow will be initiated only in the more confined reaches. The limited surface flow in winter 2004–05 did cause minor incision in a small proportion of the cross-sections, but this change was negligible when averaged over the active cross-section. Similarly, there was some bank collapse between October 2004 and November 2005, but this material caused little aggradation because the volume of collapsing material was small relative to the 16 m average width of the channels. Surface flow becomes progressively less likely in the downstream direction as the width of the valley bottom and the projected volume of alluvial deposits both tend to increase toward the mouth of Saloon Gulch. This means that nearly all of the sediment deposited in the ephemeral channels following the Hayman fire will remain in long-term storage rather than being exported to the South Platte River (Figure 35).

Unlike the ephemeral channels, the perennial channels will continue to transport post-fire sediment during Phase II because the fine post-fire deposits are easily entrained even by relatively low flows. Snowmelt runoff is the primary driver of long-term post-fire sediment evacuation in both the northern (Legleiter et al., 2003) and southern (Reneau et al., 2007) Rocky Mountains because the duration and magnitude of snowmelt flows is much greater than peak flows caused by typical summer storms (Troendle and Bevenger, 1996; Reneau et al., 2007). The volume of snowmelt runoff increases after high severity wildfires because canopy interception is nearly eliminated, and the decrease in evapotranspiration reduces the available capacity for snowmelt storage in more humid environments (Troendle and King, 1985; Troendle and Bevenger, 1996). Peak snowmelt runoff increases because the snowpack is more exposed to solar radiation (Helvey, 1980) and wind (Baker, 1986). These increases in snowmelt runoff will decrease over the duration of Phase II as a mature forest becomes re-established and the watersheds enter Phase III.

Between October 2004 and November 2005 the net ΔMBE was -3.0 cm in the perennial channels (Table 13). Snowmelt runoff and baseflows were contained within the low flow channel, so nearly all of this cross-sectional change was concentrated in a small portion of the active channel. The perennial channels incised during the winter of 2004–05, and if the mean ΔMBE for this season is extrapolated to all the perennial reaches in Brush Creek, approximately 1300 m^3 of sediment was exported to the South Platte River. This converts to approximately 22 m^3 day^{-1} if it assumed that most of the incision occurred in April and May. In late summer 2005 baseflows continued to deposit sediment from upstream in the study reaches, demonstrating that the bed was mobile even at very low flows.

The net aggradation in the perennial channels during Phase I was estimated to be approximately 11 cm. The incision from average snowmelt runoff is estimated to be approximately 2.1 cm, but this is partially balanced by 1.5 cm of aggradation during the summer season as a result of collapsing banks and sediment transport from upstream areas. Hence, the initial annual incision rate for Phase II is about 0.6 cm. Extrapolating from this rate, all of the post-fire sediment would be evacuated in approximately 18 years.

However, the terraces that have formed in the less confined reaches as a result of the valley-wide deposition and subsequent down-cutting after the Hayman fire are expected to store some of the post-fire sediment (Table 13). Because the peak snowmelt discharge was contained within the low flow channel in the large snowmelt year of 2004–05 and the terraces will eventually become stabilized by vegetation, this stored sediment will be eroded only when the channels laterally migrate. Therefore some of these post-fire terraces will persist as a long-term legacy of the fire (Benda et al., 1998; Moody and Martin, 2001b) and this could last for thousands of years as documented in Yellowstone National Park (Meyer et al., 1995). The proportion of sediment that will be stored long-term might be estimated from the relationship between drainage area and sediment delivery. Sediment delivery ratios from ten regions worldwide (Walling, 1983) and from northwestern Colorado (Hadley and Shown, 1976) suggest that 45–75% of the eroded sediment will remain in the 6.0 km^2 Brush Creek watershed. The proportion stored in Brush Creek will probably be no more than half this amount because those sediment delivery ratios are primarily from agricultural areas with less vertical relief and lower channel slopes.

The supply of readily-transported sediment will decrease over time as the fine sediment is preferentially removed and the bed coarsens (Knighton, 1998; Lisle et al., 2000), leading to an exponential decline in the rate of sediment evacuation (Figure 35) (Schumm and Rea, 1995; Lisle and Church, 2002). Adjusting the 18 year evacuation estimate for some long-term storage and the declining sediment transport rate, the in-channel post-fire sediment is expected to be evacuated from Brush Creek within about 20–40 years (Table 13). Once this sediment has been removed, the particle-size distribution of the channel bed should resemble its pre-fire state (Figure 13). No further incision should occur and the drainage network will enter the undisturbed Phase III state, assuming that stormflows and snowmelt runoff have returned to pre-fire levels.

The 20–40 year estimate for channel recovery is supported by observations after the 1986 wildfires in and around Yellowstone National Park. Aggradation occurred in the first-order channels after the fire, but the post-fire sediment was evacuated within a decade (Ernstrom, 1999). The second- to fourth-order channels also initially aggraded, but had become incised relative to unburned channels within 12–13 years (Legleiter et al., 2003). The mean annual snowfall in those watersheds is approximately 2.5 times greater than the snowfall in this study area (US NPS, 2004), and the duration of snowmelt runoff is approximately four months (Troendle and Bevenger, 1996) as compared to two months in the Plum Creek watershed near the Hayman fire. These differences suggest that the recovery time for the perennial channels in this study will be at least twice as long. However, the recovery time could be somewhat longer because the post-fire sediment in Brush Creek is generally coarser than the post-fire sediment in the Yellowstone channels (E. Wohl, Colorado State University, pers. comm., 2008). The amount of deposition in the Yellowstone watersheds is unknown, but the more rapid hillslope recovery rate and published erosion data suggest that there was less deposition after the Yellowstone fire than the Hayman fire.

The predicted residence time for post-fire deposits is approximately 300 years in the nearby Spring Creek watershed (Moody and Martin, 2001b). However, this is probably much longer than the residence time for sediment in the low flow Brush Creek channel because: (1) hillslope sediment production rates were about twice as high after the Buffalo Creek fire (Moody and Martin, 2001b; Pietraszek, 2006), so the volume of sediment stored in the Spring Creek channel and the adjacent valley bottom is believed to be much larger than in Brush Creek; (2) the Spring Creek estimate includes the sediment stored in floodplains and terraces, whereas the Brush Creek estimate includes only sediment in the low flow channel; and (3) the rate of sediment evacuation in Spring Creek was slowed by large cobbles in the post-fire sediment (D_{84} ~128 mm, D_{95} ~256 mm) that armored the channel bed and were immobile during snowmelt runoff (Moody and Martin, 2001c). In Brush Creek the D_{95} was only about 45 mm, and field observations in early April through late May 2005 showed that these particles were entrained and transported 10 m or more by snowmelt runoff. The paucity of clasts larger than 45 mm means that a stable armor layer is unlikely to form until the stream incises down to its pre-fire channel.

During Phase II, Brush Creek will have a continuing effect on water quality and downstream reservoir storage because it will continue to deliver sediment to the South Platte River for decades. In contrast, Saloon Gulch will have little effect on the South Platte River because the absence of surface runoff will keep the remaining sediment in long-term storage.

5.4. WILDFIRE AS A CONTROL ON LONG-TERM VALLEY MORPHOLOGY

Before European settlement wildfires occurred about every 20–50 years in the ponderosa pine forests in the Colorado Front Range (Kaufmann et al., 2000; Veblen et al., 2000; Romme et al. 2003). Between 1500 and 1880, the largest patch of high-severity, stand-replacing fire in the Cheesman area was no larger than 1.5 km^2 (Romme et al., 2003). The Hayman fire caused a 3.8 km^2 high-severity burn in the Brush Creek watershed; a stand-replacing fire at this scale has no historical precedent in the Cheesman area, and hence a recurrence interval of at least 500 years. If post-fire landforms persist beyond the wildfire recurrence interval, successive wildfires will have an important cumulative impact on watershed morphology (Moody and Martin, 2001b).

Rills and gullies preferentially remove material from the swale axes, whereas the ridgetops are less affected by post-fire erosion. Although the rills and gullies will cease to be identifiable channels within about 50–100 years, they will not completely refill with colluvium for millennia (Moody and Martin, 2001b). The recurrence interval for high-severity wildfires in this environment is less than the refilling time for these transient drainages (Moody and Martin, 2001b), so multiple wildfires would lower the swale bottoms relative to the ridgetops, thereby increasing the depth of the swales (Table 13; Figure 37).

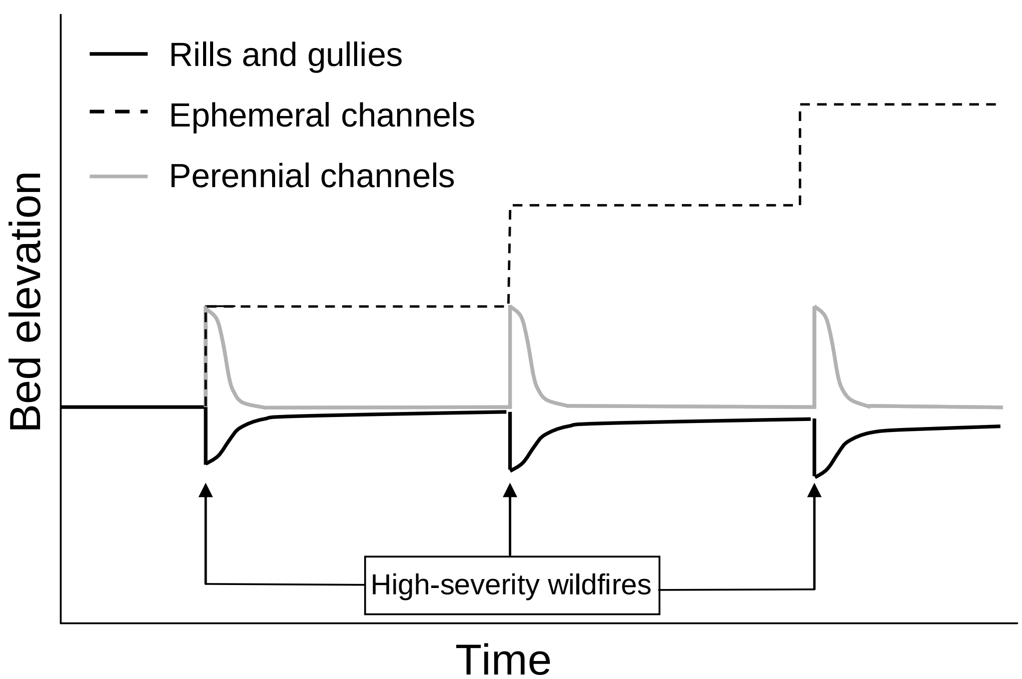


Figure 37. Conceptual model of thalweg elevation change over multiple wildfires for rills in the swale axes and gullies, ephemeral channels, and perennial channels. Axes not to scale.

In the downstream areas, previous wildfires and floods are the likely cause of the pre-Hayman fire terraces along some of the ephemeral and perennial channels. The coarser fraction of the pre-fire terraces was nearly identical in its particle-size distribution to the coarse fraction of the Hayman fire deposits, and the particle-size distributions for particles smaller than 2 mm were very similar (Figure 25). Because post-fire terraces may persist for thousands of years (Meyer et al., 1995), particle breakdown caused by soil forming processes could account for the small differences in the fine fraction (Wohl and Pearthree, 1991). The areas of greatest aggradation after the Hayman fire were generally adjacent to the largest pre-fire terraces, and this further indicates that the pre-fire terraces were formed by floods after a high severity wildfire. Although no ash layer was present in the pre-Hayman terraces to definitively identify post-fire floods as the formative agent, field observations from this and other studies indicate that ash is readily flushed downstream and out of small watersheds by the initial floods (Meyer et al., 1995; Moody and Martin, 2001c).

Over time the sediment from wildfires is expected to progressively increase the bed elevation of the ephemeral channels (Figure 37). This sediment will persist because runoff from all but the most extreme storms is transmitted through the deep alluvial deposits as subsurface flow (Figure 38). In the absence of surface runoff, the aggradation from successive wildfires will progressively increase the depth of alluvium and the valley bottom width in the ephemeral watersheds (Figure 37).

The 1–2 m knickpoints at the outlets of the Saloon Gulch and Scraggy View Gulch watersheds demonstrate that a large proportion of the sediment from previous fires remains stored in these watersheds. The Saloon Gulch knickpoint re-formed after each

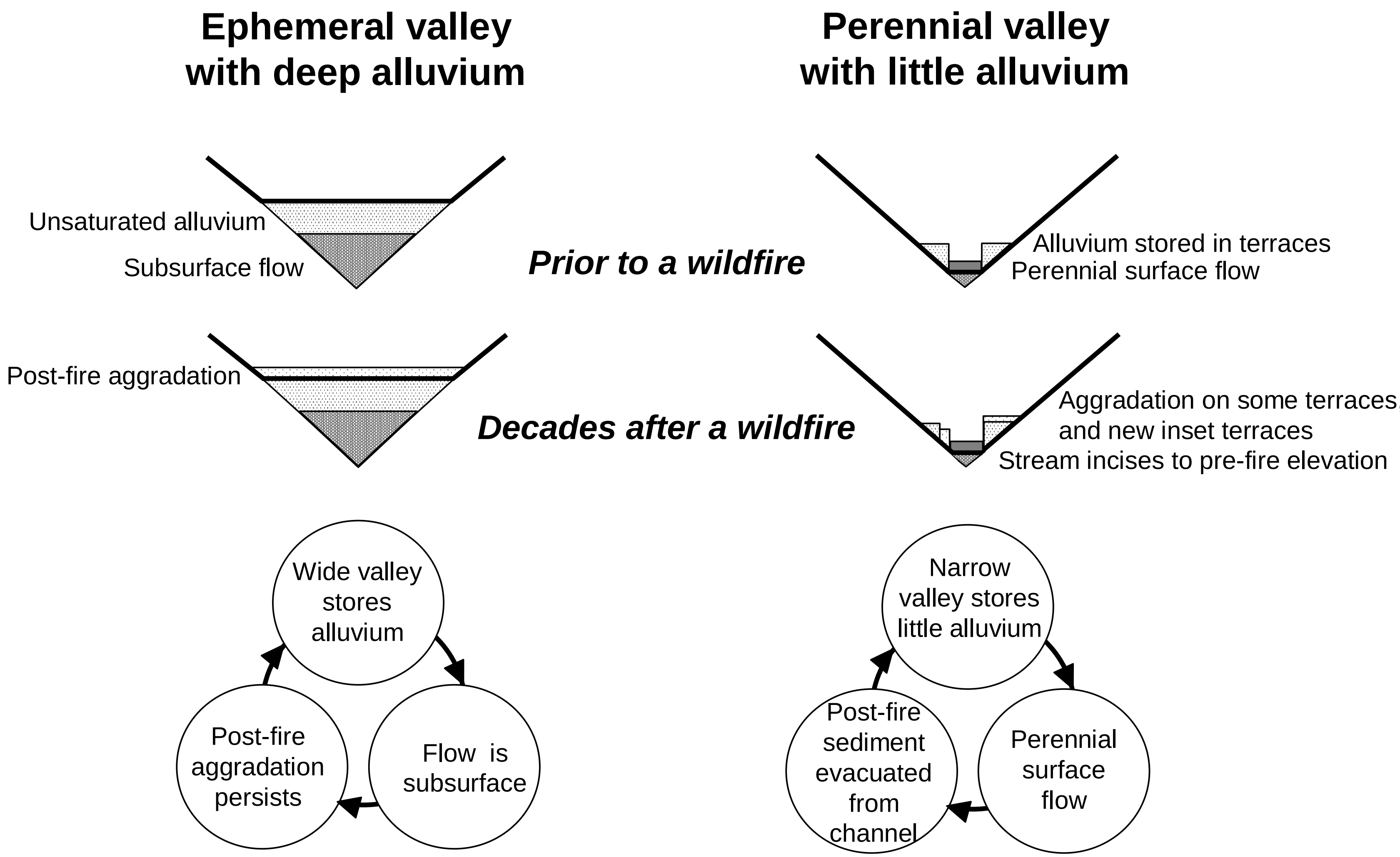


Figure 38. A conceptual model in which the width of the valley floor, flow regime, and post-fire change in valley elevation create a positive feedback loop that reinforces pre-fire differences between the study watersheds.

post-Hayman flood when the alluvial fan was truncated by the South Platte River. The knickpoints persist because there is little or no surface flow or fluvial sediment transport in the aggraded ephemeral channels after the initial Phase I response. The abrupt change in elevation between these two tributary watersheds and the South Platte River indicates that the cycles of incision and aggradation in the tributaries are out of phase because these channels are geomorphically isolated from the South Platte River (Schumm, 1977). In the absence of perennial flows or regular storm runoff, the valley floor elevations in Lower Saloon Gulch and Scraggy View Gulch are controlled by the episodic deposition of post-fire sediment (Figure 37) rather than the base level of the South Platte River.

Valley width and channel confinement appear to be important controls on the flow regime and long-term geomorphology of these watersheds. The average width of the valley floor in Lower Saloon Gulch was 66 m, indicating deep alluvial deposits. Within the main channels, the ephemeral reaches had significantly wider valleys ($p=0.001$) and lower confinement ($p<0.0001$) than the perennial reaches. The extent of the alluvial deposits in Lower Saloon Gulch and associated capacity for subsurface flow (Figure 38) probably explain why there was only surface flow in the narrowest reach, where the valley was just 20 m wide.

The width of the valley floor, the absence of perennial surface flow, and the persistent aggradation after high-severity fires create a positive feedback loop in the ephemeral channels (Figure 38). Wide reaches store deep alluvium on the valley floor, therefore baseflows are transmitted beneath the surface. Due to the lack of downstream fluvial sediment transport during Phase II and Phase III, the post-fire sediment deposited in Phase I is stored in the watershed. The additional deposits increase the valley width and the transmissivity of the alluvium (Laird and Harvey, 1986), increasing the probability that aggradation from future fires will persist, and diminishing the likelihood that an extreme storm could cause surface runoff and begin to evacuate the stored sediment (Figure 38).

The absence of a knickpoint before the Hayman fire demonstrates that Brush Creek was in phase with the South Platte River. This means that, despite episodic disturbance from wildfires and floods, the rate of sediment delivery in Lower Brush Creek has continually re-adjusted to the base level of the South Platte River. Jenny Gulch did not have perennial flow at the watershed outlet, but there was no knickpoint at the confluence with the South Platte River. Since the main channel in Jenny Gulch was 71% perennial by length, flow at the watershed outlet probably occurs with sufficient frequency after wildfires that the channel remains in phase with the South Platte River. Therefore the influence of wildfires on the valley morphology of these predominantly perennial watersheds is transient except for the formation and rejuvenation of terraces at the margins of the valley floor.

The interactions between a narrow valley width, perennial flow, and the evacuation of post-fire sediment is believed to form a self-sustaining feedback loop for the perennial channels in this study. The average width of the valley floor in Lower Brush Creek was only 10 m, and the narrow reaches store little alluvium on the valley floor. Consequently, the alluvium remains saturated and surface flow is perennial (Figure 38). The perennial flow means that sediment deposited in the low flow channel during Phase I will be evacuated, thereby ensuring that the valley remains narrow with only limited alluvial deposits. Any terraces that remain along the valley margins further confine the channel. The capacity of the low flow channel to evacuate post-fire sediment ensures that the channel remains narrow and confined after a wildfire, which are the conditions that perpetuate perennial surface flow (Figure 38).

5.5. RECOMMENDATIONS

Public land managers spent over $20,000,000 after the Hayman fire to minimize the adverse effects of the wildfire on floods, water quality, wildlife habitat, recreational resources, and downstream public water infrastructure (Kent et al., 2003). The hillslope treatments that reduced hillslope erosion, such as straw or hydromulch, were effective primarily because they increased ground cover and thereby reduced surface runoff (Wagenbrenner et al., 2006; Pietraszek, 2006; Rough, 2007). By reducing the amount of surface runoff, carefully-selected hillslope treatments also should reduce post-fire incision and sediment production from the rills and gullies, and therefore the amount of downstream aggradation.

This study identified the range of slopes and contributing areas associated with channel heads, as well as the decrease in slope and the range of contributing areas associated with the gully-channel transitions. Following a high-severity wildfire, an analysis of high-resolution digital terrain data could be used to predict the likely extent of the incising channel network. The results could help direct hillslope treatments to those areas that are most likely to develop rills and gullies, which is where the post-fire treatments would be most effective.

The results of this study indicate that perennial watersheds such as Brush Creek can continue to affect downstream channels and water quality even after Phase I is complete. The duration of these effects over time is largely unknown, but the volume of sediment evacuated from the perennial channels by snowmelt and baseflows in the coming decades is likely to exceed the volume of sediment evacuated by summer floods during Phase I. Additional research is needed to quantify the duration and magnitude of sediment delivery from small perennial watersheds after high severity wildfires.

Data also are needed on the sediment delivery rates at larger scales, as these are of most interest to water managers. After the Hayman fire Denver Water constructed sediment detention structures in the 500 km^2 Goose Creek watershed and the 75 km^2 Turkey Creek watershed. The goal was to capture post-fire sediment before it reached Cheesman Reservoir (J. Gaborek, Denver Water, pers. comm., 2003). These structures have been cleared of sediment on an annual basis (Hartman, 2007), and a continuing analysis of the annual sedimentation rates could greatly improve our understanding of the timing and duration of post-fire sediment delivery at these larger scales. The sedimentation data from these larger watersheds also can be compared to the sediment yields being measured in several 3–5 ha sub-watersheds of Turkey Creek (MacDonald and Robichaud, 2007). Semi-annual bathymetric surveys could be used to compare sediment delivery rates from summer storms and snowmelt runoff. These data, when combined with the construction and maintenance costs, could be used to compare the known costs and effectiveness of hillslope treatments (Wagenbrenner et al., 2006; Rough, 2007; MacDonald et al., in press) against the costs of in-channel sediment detention structures. Such information would help water resources managers maximize their return on investment when trying to protect water quality and the water supply infrastructure after a high severity fire.

Additional research also is needed to evaluate the effect of post-fire soil water repellency on runoff at the watershed scale during Phase I. Recent research suggests that soil sealing on bare hillslopes is the primary cause of post-fire runoff at the hillslope scale in the Colorado Front Range after high severity wildfires (Larsen et al., in review), but the results from this study suggests that post-fire soil water repellency was a control on flood magnitudes in the third summer after burning. Additional research on the spatial distribution and strength of soil water repellency over time is needed to better understand the underlying cause(s) of the increase in runoff after high severity fires. This information could then be used to better predict the effects of fires on runoff, and to help design more effective post-fire rehabilitation treatments.

6. CONCLUSIONS

From May 2004 to November 2005 post-fire changes in rills, gullies, ephemeral channels, and perennial channels were studied in two watersheds in the Colorado Front Range that burned in the 2002 Hayman fire. Cross-sections were re-surveyed after each storm and at the end of each season, and particle size data were collected from the hillslopes, terraces, and the active channels. Channel head and reach-scale geomorphic data were collected in the two burned watersheds and two similar unburned watersheds to assess the morphological changes in the drainage network that had occurred since the fire as a result of the increased flows and extensive hillslope erosion.

Drainage network change was initially driven by summer convective storms, and rainstorms with a mean maximum I_{30} greater than 14 mm hr^{-1} generally caused basin-wide flooding in Saloon Gulch in summer 2004. The magnitude of cross-sectional change decreased with increasing antecedent moisture, suggesting that soil water repellency was an important control on flood size and hence net cross-sectional change.

The floods in summer 2004 generally caused incision in the hillslope rills and gullies and deposition in the downstream ephemeral and perennial channels. The change in mean bed elevation was spatially and temporally variable, and most of the aggradation in the downstream channels occurred in three lower gradient reaches. The greatest magnitude of cross-sectional change during the 18-month monitoring period occurred in summer 2004. This summer represented the last part of the initial Phase I response, during which summer convective storms cause incision in headwater channels and flooding and deposition in downstream channels.

Summer 2005 was relatively dry, so cross-sectional change during the winter of 2004–05 and summer 2005 was driven by snowmelt runoff, baseflows, and colluvial processes. The rills and gullies aggraded slightly, and this was primarily due to bank collapse. There was almost no incision or deposition in the ephemeral channels because most reaches had no surface flow. In contrast, the perennial channels incised during snowmelt runoff. The changes in the magnitude and direction of cross-sectional response between summer 2004 and summer 2005 signal the end of the initial Phase I response to the Hayman fire, and the beginning of the Phase II response, which is when hillslope recovery greatly reduces surface runoff and erosion rates, and hence the likelihood of watershed-wide flooding in response to summer thunderstorms.

The differences between the drainage networks in the burned and unburned watersheds illustrate the combined effect of the Phase I and Phase II responses from summer 2002 to summer 2005. In the two burned watersheds, the overland flow from summer convective storms incised rills and gullies on previously unchannelized hillslopes. The mean contributing area for channel heads in the burned watersheds was three orders of magnitude smaller than in the unburned watersheds. Downstream in the burned watersheds, the newly-incised hillslope gullies became aggrading channels where the local slope decreased from an average of 16% to an average of 10%. In the burned watersheds the main channels were four times wider than in the unburned watersheds, and the banks were poorly vegetated with much higher rates of bank cutting and instability. Knickpoints were nearly ten times more frequent in the burned watersheds, and this indicates rapid channel adjustments to the increase in peak flows and sediment supply. When stratified by flow regime, the burned watersheds had much more fine material in the channels, and this is due to the large volumes of newly-deposited sediment.

In summer 2006 there were no floods despite several large and intense storms. This confirms the end of the initial response phase, and the data collected after October 2004 can help predict the time required for the drainage network to recover (Phase II). During Phase II the rills and gullies will begin to refill with colluvium from the hillslopes and bank collapse, and they are expected to have largely disappeared within a century. In the absence of surface flow, the ephemeral channels will not measurably aggrade or incise, and the volume of colluvium from hillslopes and bank collapse will be too small to affect the elevation of these wide channels.

Snowmelt runoff, stormflows, and baseflows are projected to evacuate the post-fire sediment from the low flow perennial channels within 20–40 years, although some sediment will remain stored in terraces because not all of the post-fire deposits can be accessed by the lower flows characteristic of Phase II. Some of these recently-formed terraces are expected to become long-term features of the landscape, since the particle-size data suggest that the pre-fire terraces also were formed by the wildfire-flood sequence.

For both the ephemeral and perennial channels, there appears to be a self-enhancing feedback loop wherein the valley form determines the flow regime and the persistence of post-fire sediment. The wide ephemeral reaches have deep alluvial deposits so most runoff is subsurface. In the absence of surface flow, the ephemeral channels simply store the post-fire sediment, which further increases the width of the valley floor, the depth of the alluvium, and the capacity to transmit subsurface flow. In the perennial channels snowmelt runoff is expected to evacuate most of the post-fire sediment within decades, ensuring that the valley floor remains narrow, the alluvium shallow, and surface flow perennial. In this fire-prone area these feedback loops explain why Lower Saloon Gulch has a wide valley floor with deep alluvial deposits, predominantly ephemeral flow, and a knickpoint at its confluence with the South Platte River, whereas Lower Brush Creek has a narrow valley floor with little alluvium, perennial flow, and no knickpoint at its outlet. The different geomorphic responses of these two watersheds to high severity fires have important implications for water managers and landscape evolution.

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APPENDIX A

Total precipitation, maximum 30-minute intensity, and erosivity of all storms greater than 5 mm for each rain gage.

USG North 1				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
18-Jun-04	18:10	10.6	18.8	44.3
23-Jun-04	12:20	7.2	5.2	4.9
29-Jun-04	16:30	16.4	32.8	141.4
29-Jun-04	19:10	5.6	4.8	3.1
30-Jun-04	17:20	5.6	4.4	3.2
14-Jul-04	17:35	23.2	42.4	252.2
15-Jul-04	15:10	10.2	18.8	43.4
16-Jul-04	16:40	11.2	4.8	6.4
23-Jul-04	16:20	11.6	12.4	24.1
19-Aug-04	2:25	6.2	3.2	2.2
21-Aug-04	13:55	10.0	18.0	39.1
27-Sep-04	21:55	16.6	13.6	33.7
12-Oct-04	23:50	5.0	3.6	2.0
24-Oct-04 to 20-May-04, no data				
25-Jul-05	19:35	7.2	6.4	6.1
4-Aug-05	11:55	10.8	8.4	11.6
9-Aug-05	17:20	5.4	10.0	9.8
16-Aug-05	15:35	5.0	9.2	7.3
22-Sep-05	16:00	8.6	13.2	20.4

USG North 2				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
18-Jun-04	18:10	9.2	16.0	32.0
23-Jun-04	10:10	9.0	5.6	6.8
29-Jun-04	16:30	15.0	20.4	58.8
14-Jul-04	17:35	19.6	36.4	179.1
15-Jul-04	15:10	8.6	15.6	30.1
16-Jul-04	16:35	6.0	3.6	2.4
23-Jul-04	16:20	10.4	12.4	22.0
21-Aug-04	14:00	9.6	17.2	35.9
27-Sep-04	21:55	13.2	10.0	18.2
2-Nov-04	10:30	5.6	2.4	1.4
21-Nov-04	11:05	8.2	3.2	2.9
21-Mar-05	12:00	8.8	6.0	6.7
11-Apr-05	10:10	12.4	6.4	9.9
25-Apr-05	10:30	20.4	6.8	17.0
30-May-05	17:00	5.0	4.4	3.4
3-Jun-05	16:45	5.2	6.8	4.7
10-Jun-05	13:10	7.2	10.0	11.2
25-Jul-05	19:35	6.4	6.4	5.6
4-Aug-05	11:55	9.0	7.2	8.0
22-Sep-05	16:00	8.2	12.8	18.9

USG South				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
18-Jun-04	18:15	12.2	22.9	64.8
20-Jun-04	12:30	6.4	12.7	19.1
23-Jun-04	10:15	7.4	13.2	19.2
27-Jun-04	16:20	7.9	14.2	21.1
29-Jun-04	19:00	6.6	6.6	5.6
30-Jun-04	17:25	5.3	3.6	2.2
9-Jul-04	20:05	5.1	10.2	12.4
14-Jul-04	17:45	13.2	23.4	67.7
16-Jul-04	16:25	9.7	5.1	5.8
19-Jul-04	19:00	5.1	4.1	2.5
23-Jul-04	15:50	12.4	9.7	18.1
19-Aug-04	2:30	8.6	4.6	4.6
21-Aug-04	14:00	12.7	24.9	75.6
27-Aug-04	13:45	5.8	11.7	13.1
9-Sep-04	1:00	12.7	25.4	89.9
25-Sep-04	19:00	6.9	11.7	13.6
27-Sep-04	21:45	21.6	15.7	54.4
4-Oct-04	17:05	5.3	9.1	7.9
13-Oct-04	0:05	5.3	3.6	2.2
13-Oct-04	11:55	8.1	8.1	9.6
24-Oct-04	6:55	9.1	18.3	42.3
27-Oct-04 to 14-Mar-04, no data				
25-Jul-05	19:35	7.2	6.0	5.6
4-Aug-05	11:50	18.6	8.4	19.4
6-Sep-05	15:40	9.0	11.6	16.3

LSG				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
21-May-04 to 22-Jun-04, no data				
23-Jun-04	10:15	6.1	9.7	10.5
23-Jun-04	13:20	8.9	4.6	5.4
29-Jun-04	16:35	18.3	24.9	90.5
14-Jul-04	17:40	16.5	31.0	124.1
15-Jul-04	15:25	11.4	20.8	56.4
16-Jul-04	16:50	11.4	4.6	6.3
19-Jul-04	19:00	6.1	4.1	3.2
23-Jul-04	16:20	17.0	19.8	65.4
5-Aug-04	16:55	9.1	17.3	34.3
21-Aug-04	14:05	11.2	20.3	48.4
27-Aug-04	13:45	6.4	11.2	14.0
31-Aug-04	19:55	9.9	19.3	43.4
21-Sep-04	9:20	5.3	2.0	1.3
27-Sep-04	22:05	18.0	11.7	32.3
13-Oct-04	0:05	15.7	5.1	9.5
30-Jan-05	14:35	7.9	6.1	6.2
21-Mar-05	12:45	10.4	13.2	23.9
11-Apr-05	13:30	8.9	15.2	26.7
24-Apr-05	15:15	8.1	2.0	1.9
25-Apr-05	13:50	25.1	7.6	26.4
29-May-05	19:50	5.6	5.6	4.0
10-Jun-05	14:30	8.1	14.2	24.1
20-Jun-05	19:40	6.4	5.6	5.5
25-Jul-05	18:50	6.1	5.6	4.3
4-Aug-05	11:05	18.0	9.1	20.8
16-Aug-05	14:40	5.1	8.6	7.1
6-Sep-05	14:45	9.4	11.2	16.3
9-Oct-05	14:30	5.1	2.5	1.5
10-Oct-05	14:20	6.4	3.0	2.1
11-Oct-05	11:00	8.6	6.6	7.3

UBC				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
18-Jun-04	18:10	14.5	25.4	86.8
20-Jun-04	12:35	8.6	17.3	35.1
23-Jun-04	10:15	20.8	16.8	58.9
25-Jun-04	16:20	6.6	11.2	12.7
29-Jun-04	19:00	8.1	7.6	8.2
30-Jun-04	17:25	5.3	3.6	2.2
14-Jul-04	17:45	6.9	12.2	15.2
16-Jul-04	16:20	15.2	5.6	10.5
23-Jul-04	15:55	22.9	26.9	127.7
19-Aug-04	2:25	7.9	3.6	3.2
21-Aug-04	14:00	7.6	14.7	23.1
27-Aug-04	13:45	5.8	10.7	11.9
27-Sep-04	21:55	19.3	11.7	32.9
13-Oct-04	0:10	6.6	4.6	3.6
13-Oct-04	11:50	9.4	9.1	13.2
24-Oct-04 to 20-May-04, no data				
24-Jun-05	21:40	8.1	13.2	21.4
25-Jul-05	18:45	7.4	6.6	6.7
4-Aug-05	10:55	19.6	9.1	22.9
16-Aug-05	14:35	6.4	9.7	9.6
6-Sep-05	15:45	8.9	12.2	17.8
11-Oct-05	10:30	10.4	4.1	5.2

LBC				
Date	Time	Precipitation (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
18-Jun-04	18:15	13.2	16.8	48.8
23-Jun-04	10:30	20.1	12.7	42.1
27-Jun-04	16:30	14.5	25.4	83.9
29-Jun-04	19:00	7.9	8.6	9.7
30-Jun-04	18:35	5.6	4.1	2.7
16-Jul-04	16:10	10.2	6.6	8.8
23-Jul-04	16:00	14.7	12.7	31.1
5-Aug-04	16:55	5.8	10.7	12.5
19-Aug-04	2:25	7.1	3.0	2.6
27-Aug-04	13:50	7.1	11.2	15.9
27-Sep-04	22:15	15.7	8.6	20.0
13-Oct-04	0:35	11.2	4.1	5.4
9-Nov-04	21:55	10.7	6.6	9.4
21-Mar-05	12:40	10.4	11.2	18.9
11-Apr-05	12:40	12.2	16.8	39.7
24-Apr-05	20:15	10.4	3.6	4.3
25-Apr-05	14:45	26.2	10.7	42.0
29-May-05	19:45	7.6	8.1	9.1
10-Jun-05	14:25	10.2	18.3	42.5
23-Jun-05	13:55	5.6	11.2	13.3
24-Jun-05	20:50	7.9	12.2	18.1
25-Jul-05	18:55	5.3	5.1	3.5
4-Aug-05	11:05	20.3	10.2	27.2
9-Aug-05	16:10	7.4	13.7	21.7
16-Aug-05	14:30	15.7	26.9	102.1
6-Sep-05	14:45	17.0	28.4	108.6
28-Sep-05	4:20	5.6	9.7	9.0
10-Oct-05	15:00	8.4	4.6	5.1
11-Oct-05	11:15	11.7	6.1	8.8

APPENDIX B

Change in cross-sectional area (ΔA), change in mean bed elevation (ΔMBE), and absolute change in mean bed elevation (|ΔMBE|) for each study reach after each flood. The annotation "n.d." indicates no data, and "n.f." indicates no flood.

		18 June 2004			29 June 2004			14 July 2004			23 July 2004			27 September 2004		
Reach ID	Watershed	ΔA (m^2)	ΔMBE (cm)	|ΔMBE| (cm)	ΔA (m^2)	ΔMBE (cm)	|ΔMBE| (cm)	ΔA (m^2)	ΔMBE (cm)	|ΔMBE| (cm)	ΔA (m^2)	ΔMBE (cm)	|ΔMBE| (cm)	ΔA (m^2)	ΔMBE (cm)	|ΔMBE| (cm)
G1	Saloon Gulch	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.010	1.8	1.8	0.005	0.8	0.8	-0.002	-0.2	0.6
G2	Saloon Gulch	0.007	1.5	1.5	-0.012	-2.7	3.4	0.016	2.0	2.0	-0.026	-3.5	3.5	0.028	4.0	5.2
G3	Saloon Gulch	-0.036	-2.2	2.2	-0.049	-3.1	3.1	0.022	1.6	2.1	-0.001	0.0	0.6	-0.053	-3.5	3.5
G4	Brush Creek	n.f.	n.f.	n.f.	0.006	0.4	2.3	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	0.009	0.0	0.0
G5	Brush Creek	n.f.	n.f.	n.f.	0.002	0.2	0.2	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	-0.018	0.0	0.0
G6	Brush Creek	n.f.	n.f.	n.f.	0.006	0.4	0.4	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	0.000	0.0	0.0
CE0.1	Saloon Gulch	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.178	2.4	2.4	0.190	2.5	2.5	-0.345	-4.6	4.6
CE0.2	Saloon Gulch	0.004	0.3	0.3	-0.009	-0.1	0.6	0.061	2.1	2.1	-0.023	-0.6	1.0	-0.003	0.1	0.5
CE0.3	Saloon Gulch	-0.018	-1.5	1.5	-0.051	-4.1	4.1	0.020	1.5	1.8	-0.016	-1.3	3.3	-0.039	-3.4	4.1
CE0.6	Saloon Gulch	0.073	0.9	2.2	-0.183	-3.5	3.5	0.085	1.7	1.7	-0.085	-3.0	3.7	-0.105	-1.7	2.8
CE1.8	Saloon Gulch	-0.390	-2.3	2.3	0.045	0.1	0.6	0.456	2.6	2.6	0.136	0.7	1.2	0.584	2.7	2.7
CE2.0	Saloon Gulch	1.508	14.8	14.8	0.039	0.3	2.4	0.920	8.2	8.2	0.114	1.0	1.0	1.013	8.9	8.9
CE2.4	Saloon Gulch	n.d.	n.d.	n.d.	0.523	0.4	2.0	0.276	0.7	1.2	-0.584	-1.2	1.2	1.351	2.4	2.4
CE2.6	Saloon Gulch	n.d.	n.d.	n.d.	-0.109	-0.5	1.3	0.219	1.2	1.4	-0.072	-0.2	0.7	0.265	1.1	1.1
CE3.1	Saloon Gulch	-0.955	-5.1	20.5	0.312	1.3	7.8	-0.781	-5.1	20.2	0.624	3.3	13.3	-0.750	-3.4	18.7
CP1.7	Brush Creek	n.f.	n.f.	n.f.	0.107	4.3	4.3	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	-0.137	-5.4	5.4
CP1.9	Brush Creek	n.f.	n.f.	n.f.	0.730	5.9	5.9	n.f.	n.f.	n.f.	n.d.	n.d.	n.d.	0.786	6.6	7.0
CP3.3	Brush Creek	n.f.	n.f.	n.f.	1.908	16.5	17.8	n.f.	n.f.	n.f.	1.655	13.8	13.8	-1.673	-15.2	15.2
CP4.1	Brush Creek	n.f.	n.f.	n.f.	-0.008	-1.0	2.5	n.f.	n.f.	n.f.	-0.035	-1.9	4.0	0.033	0.8	2.7
CP4.2	Brush Creek	n.f.	n.f.	n.f.	-0.086	-1.7	5.7	n.f.	n.f.	n.f.	-0.002	0.0	2.7	-0.086	-2.1	2.1
CP4.3	Brush Creek	n.f.	n.f.	n.f.	0.103	1.5	1.7	n.f.	n.f.	n.f.	0.013	0.6	0.6	-0.090	-1.3	1.3

APPENDIX C

Contributing area and slope above and below the channel heads in unburned and burned watersheds.

	Channel Head ID	Contributing area (ha)	Slope above (%)	Slope below (%)
Unburned	UB1	56	12	16
	UB2	9	20	19
	UB3	87	19	13
	UB4	18	14	12
Burned	B1	0.153	17	15
	B2	0.023	32	35
	B3	0.060	39	38
	B4	0.008	24	25
	B5	0.070	27	25
	B6	0.055	24	25
	B7	0.048	18	24
	B8	0.025	28	32
	B9	0.030	21	24
	B10	0.058	21	22
	B11	0.018	23	21
	B12	0.055	29	28
	B13	0.035	31	35
	B14	0.020	18	17

APPENDIX D

Contributing area and slope above and below the gully-channel transitions in the burned watersheds.

	ID	Contributing area (ha)	Slope above (%)	Slope below (%)
Saloon Gulch	SGT1	4.96	12	8
	SGT2	0.31	15	9
	SGT3	7.80	16	11
	SGT4	2.51	17	9
	SGT5	2.16	15	10
	SGT6	5.29	16	9
	SGT7	3.49	16	12
	SGT8	1.89	8	8
	SGT9	2.44	24	14
	SGT10	0.31	14	10
	SGT11	5.25	14	7
	SGT12	8.59	14	7
Brush Creek	BCT1	1.79	12	11
	BCT2	5.90	16	5
	BCT3	2.52	16	13
	BCT4	9.89	17	11
	BCT5	3.68	17	12
	BCT6	1.68	17	13
	BCT7	0.76	18	12
	BCT8	5.57	18	11
	BCT9	6.02	18	11
	BCT10	3.29	16	13
	BCT11	6.72	22	6
	BCT12	6.60	12	13
	BCT13	6.19	15	10
	BCT14	5.57	17	10
	BCT15	12.36	16	11
	BCT16	1.86	15	9
	BCT17	5.20	23	14
	BCT18	5.06	13	12
	BCT19	6.49	22	13
	BCT20	6.00	13	11

APPENDIX E

Channel characteristics for the main channels reaches in burned watersheds (Saloon Gulch and Brush Creek) and the unburned watersheds (Jenny Gulch and Scraggy View Gulch).

Saloon Gulch												
Reach ID	Contributing area	Length	Active width	Valley width	Slope	Depth	Number of channels	Surface flow	Bed material	Knickpoints	Bank Vegetation	Bank Condition
	(km^2)	(m)	(m)	(m)	(%)	(m)	1=single 2=multiple	1=present 2=absent	1=fine 2=coarse 3=bedrock	(count)	1<25% 2=25-50% 3>50%	1=eroding into pre-fire material 2=eroding into post-fire material 3=eroding into both 4=stable
SG-1	0.16	76	0.8	4.2	7	0.12	1	2	1	0	3	4
SG-2	0.18	70	1.5	9.7	19	0.01	1	1	1	1	3	1
SG-3	0.19	67	1.4	6.1	14	0.30	1	1	1	2	2	1
SG-4	0.26	144	0.6	10.4	20	0.35	1	1	3	3	3	1
SG-5	0.34	71	1.1	9.8	20	0.27	1	1	3	0	3	1
SG-6	0.36	77	4.2	13.2	10	0.75	1	1	1	0	1	1
SG-7	0.37	74	9.7	18.2	10	0.39	2	2	1	1	2	2
SG-8	0.41	188	3.0	3.0	10	0.89	1	1	1	2	3	1
SG-9	0.47	259	3.4	5.0	9	0.73	1	1	1	0	1	2
SG-10	0.74	381	5.7	17.9	11	0.36	1	2	1	3	2	1
SG-11	1.03	302	8.3	14.3	11	0.48	1	2	1	1	2	4
SG-12	1.09	105	1.0	1.0	12	0.30	1	1	3	0	1	4
SG-13	1.22	106	6.0	6.0	14	0.89	1	1	1	0	1	4
SG-14	1.41	93	12.0	48.3	11	0.78	1	2	1	0	1	1
SG-15	1.41	369	6.5	6.5	15	1.50	1	1	3	0	2	1
SG-16	1.48	75	7.9	7.9	8	1.58	1	1	1	0	1	4
SG-17	1.50	60	6.7	21.5	9	0.28	1	2	1	0	1	4
SG-18	2.22	231	17.4	45.0	10	0.38	1	2	1	2	1	4
SG-19	2.30	95	12.2	20.4	8	1.80	1	1	1	1	1	3
SG-20	2.33	108	10.5	18.4	8	0.23	1	2	1	0	2	1
SG-21	2.79	396	25.6	103.0	10	0.26	2	2	1	4	2	1
SG-22	3.32	470	17.0	64.5	9	0.20	1	2	1	1	3	4
SG-23	3.42	189	26.6	47.2	10	0.90	2	2	1	3	3	1

Brush Creek												
Reach ID	Contributing area	Length	Active width	Valley width	Slope	Depth	Number of channels	Surface flow	Bed material	Knickpoints	Bank Vegetation	Bank Condition
	(km^2)	(m)	(m)	(m)	(%)	(m)	1=single 2=multiple	1=present 2=absent	1=fine 2=coarse 3=bedrock	(count)	1<25% 2=25-50% 3>50%	1=eroding into pre-fire material 2=eroding into post-fire material 3=eroding into both 4=stable
BC-1	0.59	169	3.8	8.3	8	0.17	1	2	1	0	3	4
BC-2	0.79	96	3.0	7.8	9	0.30	1	1	1	0	3	1
BC-3	0.97	242	1.4	3.5	9	0.44	1	1	1	1	3	1
BC-4	1.09	202	2.2	14.7	8	0.56	1	1	3	1	1	2
BC-5	1.25	240	17.2	51.5	8	0.26	2	2	1	0	3	4
BC-6	1.53	59	5.2	100.0	7	1.26	1	2	1	2	3	1
BC-7	1.87	258	3.7	24.8	7	0.23	1	2	1	0	3	4
BC-8	2.12	208	7.4	7.4	7	0.76	1	1	1	1	1	2
BC-9	2.33	42	2.7	31.0	9	0.68	1	1	1	0	2	2
BC-10	2.52	263	6.3	6.3	11	0.85	1	1	1	1	1	2
BC-11	2.62	144	13.6	30.1	6	1.25	1	1	1	0	1	3
BC-12	3.11	144	6.9	15.2	9	0.62	1	2	1	0	2	1
BC-13	3.54	164	3.2	3.2	6	0.71	1	1	2	1	3	1
BC-14	3.79	276	10.5	25.1	6	1.08	1	1	1	0	1	2
BC-15	4.08	211	3.4	6.0	6	0.71	1	1	1	1	3	3
BC-16	4.20	321	4.7	6.0	35	0.77	1	1	3	0	1	1
BC-17	4.25	73	6.7	6.7	5	1.40	1	1	1	0	1	3
BC-18	4.65	194	4.5	13.8	7	1.19	1	1	2	1	2	1
BC-19	5.07	120	9.6	10.5	6	0.89	1	1	2	0	2	1
BC-20	5.16	156	3.6	11.1	6	1.01	1	1	2	0	3	1
BC-21	5.30	233	11.0	11.0	5	0.99	1	1	1	0	1	2
BC-22	5.40	116	9.2	9.5	9	0.98	1	1	2	0	3	1
BC-23	5.50	131	4.4	4.9	6	1.65	1	1	2	0	3	1
BC-24	5.58	87	4.2	14.2	6	1.17	1	1	2	0	2	1
BC-25	5.69	248	5.6	10.1	8	1.35	1	1	2	1	2	1
BC-26	5.80	37	6.3	6.3	7	0.80	1	1	1	0	1	1
BC-27	5.81	22	2.3	2.3	27	0.01	1	1	3	0	1	1
BC-28	5.90	283	6.8	7.3	7	1.21	1	1	2	0	2	1
BC-29	6.01	49	2.9	9.2	9	0.97	1	1	2	0	3	1
BC-30	6.04	106	7.1	7.1	8	0.86	1	1	2	1	2	1
BC-31	6.09	93	2.5	7.6	10	0.59	1	1	2	0	3	1
BC-32	6.14	136	3.4	3.4	9	0.81	1	1	2	0	3	1
BC-33	6.16	28	6.6	28.0	17	0.32	2	1	2	0	3	2

Jenny Gulch												
Reach ID	Contributing area	Length	Active width	Valley width	Slope	Depth	Number of channels	Surface flow	Bed material	Knickpoints	Bank Vegetation	Bank Condition
	(km^2)	(m)	(m)	(m)	(%)	(m)	1=single 2=multiple	1=present 2=absent	1=fine 2=coarse 3=bedrock	(count)	1<25% 2=25-50% 3>50%	1=eroding into pre-fire material 2=eroding into post-fire material 3=eroding into both 4=stable
JG-1	0.87	107	1.0	19.2	7	0.37	1	3	1	0	3	4
JG-2	0.96	188	0.6	3.4	10	0.23	1	3	1	0	3	4
JG-3	1.07	217	6.0	24.8	11	1.71	1	3	1	0	3	4
JG-4	1.15	193	3.2	29.0	10	0.53	2	3	1	0	3	4
JG-5	1.26	80	9.6	78.0	14	1.70	1	3	1	0	3	4
JG-6	1.77	393	0.4	3.4	7	0.23	1	1	2	0	3	4
JG-7	2.61	768	1.1	2.7	10	0.35	1	1	2	0	3	4
JG-8	3.07	213	10.9	0.8	10	0.39	1	1	2	0	3	4
JG-9	3.26	174	1.1	14.1	10	0.62	1	1	1	0	3	4
JG-10	3.46	227	1.3	5.3	15	0.65	1	1	2	0	3	4
JG-11	3.60	122	0.9	7.3	8	0.45	1	1	2	0	3	1
JG-12	3.68	134	3.3	3.3	12	0.58	1	1	2	0	3	4
JG-13	3.75	173	1.1	5.5	7	0.42	1	1	2	0	3	4
JG-14	3.82	109	1.2	8.0	6	0.72	1	1	2	0	3	4
JG-15	3.85	132	0.7	3.5	10	0.37	1	1	2	0	3	4
JG-16	4.08	204	0.8	2.3	14	0.51	1	1	2	0	3	4
JG-17	4.36	297	0.6	4.6	8	0.29	1	1	1	0	3	4
JG-18	4.47	196	1.6	7.4	8	0.33	1	1	1	0	3	4
JG-19	4.53	145	3.2	9.0	7	0.53	1	3	2	1	3	4
JG-20	4.57	268	1.1	3.3	10	0.19	1	3	2	0	3	4
JG-21	4.59	68	2.3	7.8	4	0.23	1	3	2	0	3	4
JG-22	4.60	48	4.8	5.2	3	0.21	1	3	2	1	2	4

Scraggy View Gulch												
Reach ID	Contributing area	Length	Active width	Valley width	Slope	Depth	Number of channels	Surface flow	Bed material	Knickpoints	Bank Vegetation	Bank Condition
	(km^2)	(m)	(m)	(m)	(%)	(m)	1=single 2=multiple	1=present 2=absent	1=fine 2=coarse 3=bedrock	(count)	1<25% 2=25-50% 3>50%	1=eroding into pre-fire material 2=eroding into post-fire material 3=eroding into both 4=stable
SV-1	0.57	37	1.6	6.2		0.04	1	3	1	0	3	4
SV-2	0.69	90	2.8	2.8		0.13	1	3	1	0	3	4
SV-3	0.71	79	0.8	0.8		0.36	1	1	1	0	3	4
SV-4	0.86	69	3.7	9.5		0.38	1	3	1	0	3	4
SV-5	1.26	308	0.4	3.7	11	0.29	1	1	1	0	3	4
SV-6	1.39	125	0.5	4.6	15	0.28	1	1	1	0	3	4
SV-7	1.44	121	0.8	4.3	12	0.20	1	3	1	0	3	4
SV-8	1.66	177	0.8	5.1	13	0.14	1	1	1	0	3	4
SV-9	1.71	121	0.7	2.0	7	0.23	1	1	1	0	3	4
SV-10	1.89	165	1.6	6.6	11	0.27	1	3	1	1	3	4
SV-11	1.92	149	1.1	4.5	9	0.13	1	3	2	0	3	4
SV-12	2.76	221	1.2	8.5	8	0.33	1	3	1	0	3	4
SV-13	2.82	119	0.7	6.0	5	0.41	1	3	1	0	3	4
SV-14	3.32	74	1.0	6.2	13	0.12	1	3	1	0	3	4
SV-15	3.41	106	0.9	7.9	9	0.22	1	1	2	0	3	4
SV-16	3.61	110	1.7	9.4	5	0.30	1	3	1	0	3	4
SV-17	3.67	69	1.7	6.3	10	0.22	2	1	1	0	3	4
SV-18	3.70	57	0.4	1.1	8	0.17	1	1	1	0	3	4
SV-19	4.19	221	2.4	22.2	7	0.30	1	3	1	0	3	4
SV-20	4.51	357	0.6	8.6	6	0.25	1	1	2	0	3	4
SV-21	4.52	68	0.5	11.9	4	0.17	1	3	2	0	3	4
SV-22	4.84	351	0.9	6.5	8	0.22	1	1	2	0	3	4
SV-23	4.88	160	1.9	8.3	10	0.73	1	3	2	0	3	4
SV-24	5.34	272	10.4	3.6	6	0.97	1	3	2	0	3	4
SV-25	5.40	160	9.6	23.2	9	1.07	1	3	2	0	3	1
SV-26	5.45	305	2.4	15.0	7	0.56	1	3	2	0	3	4

APPENDIX F

Pebble count data for samples in Brush Creek reach C_P3.0 in July and November 2005. Values are the number of clasts in each size class.

Date	Cross-section	Location	<2 mm	<2.8 mm	<4 mm	<5.6 mm	<8 mm	<11 mm	<16 mm	<22.6 mm	<32 mm	<45 mm	<64 mm	<90 mm	<128 mm	<180 mm	>180 mm
July 2005	C_P3.0B	terrace	9	3	12	19	28	19	12	5	1	0	0	0	0	0	0
July 2005	C_P3.0B	channel bed	3	3	1	16	17	25	17	11	9	2	4	2	0	0	0
November 2005	C_P3.0B	channel bed	1	1	4	9	30	14	27	7	8	8	7	7	0	0	1
July 2005	C_P3.0D	terrace	3	8	11	29	24	17	24	8	3	2	0	1	0	0	0
July 2005	C_P3.0D	channel bed	9	1	4	16	15	19	18	7	7	5	4	1	0	0	0
November 2005	C_P3.0D	channel bed	17	2	11	19	15	11	17	5	5	8	3	3	0	1	0
July 2005	C_P3.0E	terrace	8	2	3	19	23	16	20	17	2	3	0	0	1	0	0
July 2005	C_P3.0E	channel bed	3	1	4	13	14	15	27	14	6	0	5	0	1	0	0
November 2005	C_P3.0E	channel bed	6	6	16	27	13	16	22	6	8	1	3	1	0	0	0

APPENDIX G

Particle size data for the bulk bed material samples taken in Saloon Gulch in September 2004 and May 2005. Values are the cumulative percent finer by weight.

Date	Cross-section	<0.063 mm	<0.125 mm	<0.25 mm	<0.5 mm	<1 mm	<2 mm	<4 mm	<8 mm	<16 mm	<24 mm
September 2004	C_E0.1a	3.9	6.9	12.2	21.0	31.7	46.5	67.8	90.9	99.6	100.0
	C_E0.2a	2.3	4.6	11.3	26.5	44.5	65.4	84.2	95.6	99.5	100.0
	C_E0.2b	2.1	4.2	7.5	16.3	31.1	54.5	79.0	94.2	100.0	100.0
	C_E0.3a	1.5	3.8	7.8	17.5	41.5	54.6	82.8	96.6	100.0	100.0
	C_E0.3c	1.2	2.8	7.6	19.2	37.9	65.3	86.1	95.9	99.6	100.0
	C_E0.6b	1.0	3.0	10.5	28.8	55.9	81.7	95.0	99.5	100.0	100.0
	C_E0.6d	1.1	3.0	7.5	19.5	40.9	72.3	92.4	97.6	100.0	100.0
	C_E1.8a	2.4	4.8	9.1	16.4	27.4	43.8	69.6	92.6	99.5	100.0
	C_E1.8b	2.6	4.8	8.6	15.7	27.9	49.6	77.8	95.9	100.0	100.0
	C_E2.0a	2.0	3.7	5.9	8.8	14.9	32.4	61.4	91.1	100.0	100.0
	C_E2.0b	2.1	4.5	7.9	15.3	30.3	50.9	79.5	96.2	100.0	100.0
	C_E2.4b	3.3	5.5	8.5	13.6	22.0	37.5	58.1	85.5	99.4	100.0
	C_E2.4c	3.5	6.1	10.3	17.2	26.6	41.0	61.2	86.0	98.5	100.0
	C_E2.6b	4.3	8.1	13.7	22.5	34.7	49.3	67.8	87.9	98.6	100.0
	C_E3.1d	2.6	4.5	8.0	16.3	29.4	48.0	78.4	97.0	99.8	100.0
May 2005	C_E0.1a	2.3	4.1	9.2	18.3	28.3	44.4	67.8	89.6	98.7	100.0
	C_E0.2a	0.6	1.6	4.1	10.1	19.1	35.9	68.3	96.6	100.0	100.0
	C_E0.3a	0.4	1.3	5.2	18.4	45.4	67.5	81.8	92.3	98.5	100.0
	C_E0.6b	0.4	1.5	5.6	17.5	38.6	63.9	85.8	98.4	100.0	100.0
	C_E0.6d	0.6	1.4	4.4	14.0	34.1	62.0	87.0	97.8	100.0	100.0
	C_E1.8a	1.1	3.5	6.9	14.3	24.6	38.9	72.7	93.3	99.3	100.0
	C_E1.8b	1.0	2.3	5.0	11.7	24.0	43.9	76.3	93.7	100.0	100.0
	C_E2.0a	0.5	1.5	3.9	9.4	18.5	34.8	64.9	90.5	100.0	100.0
	C_E2.0b	0.5	1.5	3.8	8.9	17.5	33.2	59.9	88.0	100.0	100.0
	C_E2.4a	0.7	1.9	4.4	9.3	15.7	25.7	45.1	80.1	98.3	100.0
	C_E2.4b	1.1	1.9	4.2	10.0	20.2	33.3	60.5	89.4	98.9	100.0
	C_E2.6b	0.6	2.4	6.6	18.2	36.1	57.2	79.5	95.0	100.0	100.0
	C_E3.1d	0.7	2.6	6.0	12.9	25.0	45.4	69.2	93.1	100.0	100.0

APPENDIX H

Particle size data from bulk samples of hillslope material, pre-fire terraces, and post-fire deposits in Saloon Gulch and Brush Creek in summer 2005. Values are the cumulative percent finer by weight. Two transects were established in C_E0.6 and C_E2.0 because there were two distinct terraces in these reaches. Transect C_P3.8 was established in a reach without cross-sections because only three of the perennial study reaches had pre-fire terraces.

Material	Reach	<0.063 mm	<0.125 mm	<0.25 mm	<0.5 mm	<1 mm	<2 mm	<4 mm	<8 mm	<16 mm	<24 mm
Hillslope	C_E0.6	0.2	2.4	8.3	18.1	31.1	46.7	69.2	88.7	100.0	100.0
	C_E0.6	0.3	4.7	13.2	23.6	34.7	49.1	71.6	93.2	100.0	100.0
	C_E1.8	0.1	2.2	10.9	24.0	36.8	50.3	68.8	87.0	98.1	100.0
	C_E2.0	0.5	4.9	16.7	28.5	37.7	49.1	65.8	79.8	91.1	100.0
	C_E2.0	1.0	6.0	12.9	21.3	31.4	45.8	69.5	91.5	100.0	100.0
	C_E2.6	0.5	2.9	10.3	23.1	38.0	56.6	79.4	95.1	100.0	100.0
	C_P1.9	0.3	3.0	9.4	17.1	26.8	40.0	64.4	88.0	98.6	100.0
	C_P3.3	0.4	2.6	6.4	11.4	18.5	31.1	55.3	81.8	98.7	100.0
	C_P3.8	0.8	5.1	12.7	22.7	34.7	51.1	71.5	90.5	100.0	100.0
	C_P4.3	0.8	3.8	9.0	17.1	27.0	41.9	63.4	85.6	99.5	100.0
Terrace	C_E0.6	0.2	1.8	8.1	21.8	35.6	52.3	73.6	93.2	99.6	100.0
	C_E0.6	0.2	1.7	6.1	15.2	27.9	45.2	80.2	98.2	100.0	100.0
	C_E1.8	0.3	3.0	8.2	15.2	24.2	35.5	55.2	81.7	99.3	100.0
	C_E2.0	0.3	2.4	6.6	13.9	44.2	58.7	77.6	97.1	100.0	100.0
	C_E2.0	0.4	3.1	9.5	18.7	28.2	42.1	65.8	87.8	99.3	100.0
	C_E2.6	0.4	2.2	6.2	13.9	25.2	40.2	62.7	85.8	98.6	100.0
	C_P1.9	0.3	4.3	14.6	27.8	41.0	55.0	73.8	90.1	100.0	100.0
	C_P3.3	0.8	3.5	11.2	19.6	27.3	39.6	62.8	87.4	98.6	100.0
	C_P3.8	0.3	1.9	7.1	19.4	36.6	53.8	72.0	84.5	93.2	100.0
	C_P4.3	0.9	2.5	7.5	17.3	26.5	34.7	46.5	69.6	97.2	100.0
Post-fire	C_E0.6	0.2	0.6	2.7	9.4	25.5	51.1	80.7	95.2	99.7	100.0
	C_E0.6	0.2	1.2	5.9	26.1	61.4	84.9	95.6	99.4	100.0	100.0
	C_E1.8	0.3	2.1	7.3	16.9	29.0	45.4	69.4	96.9	99.7	100.0
	C_E2.0	0.3	1.4	4.7	13.9	32.3	54.2	82.6	96.8	99.5	100.0
	C_E2.0	0.3	1.6	4.8	9.9	17.6	30.3	57.0	88.2	99.6	100.0
	C_E2.6	0.5	2.8	7.6	16.2	27.0	43.6	71.8	94.4	100.0	100.0
	C_P1.9	0.1	0.7	3.4	11.2	23.8	42.3	71.1	93.6	99.7	100.0
	C_P3.3	0.2	1.2	3.5	9.5	24.0	44.2	69.0	89.6	99.6	100.0
	C_P3.8	0.2	0.9	4.7	13.9	23.8	35.4	52.0	70.8	89.6	100.0
	C_P4.3	0.3	2.0	6.9	14.5	24.5	37.9	57.9	77.3	94.0	100.0