THESIS

EFFECTS OF THINNING AND A WILDFIRE ON SEDIMENT PRODUCTION RATES, CHANNEL MORPHOLOGY, AND WATER QUALITY IN THE UPPER SOUTH PLATTE RIVER WATERSHED

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ZAMIR LIBOHOVA ENTITLED EFFECTS OF THINNING AND A WILDFIRE ON SEDIMENT PRODUCTION RATES, CHANNEL MORPHOLOGY, AND WATER QUALITY IN THE UPPER SOUTH PLATTE RIVER WATERSHED BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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ABSTRACT OF THESIS

EFFECTS OF THINNING AND A WILDFIRE ON SEDIMENT PRODUCTION RATES, CHANNEL MORPHOLGY, AND WATER QUALITY IN THE UPPER SOUTH PLATTE RIVER WATERSHED

The Upper South Platter River watershed is the primary source of Denver's water supply. There has been increasing concern over the potential adverse effects of large wildfires on water resources and aquatic life. The initial goal of this study was to evaluate the effects of thinning on runoff and sediment production at the hillslope and small catchment scales.

Measurements of precipitation, sediment production rates, channel morphology, and water quality began in mid-2001. Sediment fences were installed to measure erosion rates from 20 paired swales and 24 road segments in three study areas--Spring Creek, Upper Saloon Gulch, and Trumbull. Contributing area, slope, ground cover, and soil particle-size distributions were measured for each swale and road segment. A larger-scale road survey assessed whether road runoff was likely to reach the stream channel network. At the catchment scale, channel characteristics were measured in four first- or second-order watersheds, and monthly grab samples were taken to characterize water quality. Flumes were installed in early summer 2002 in the 6.2 km^2 Brush Creek watershed and the 3.4 km^2 Saloon Gulch watershed.

In 2001, only 3 of 40 swales produced sediment, while the 17 of the 24 road segments produced sediment. The average road sediment production rate was 2.1 kg m^{-2} in 2001 and 0.5 kg m^{-2} in 2002. Less than 20% of the roads in Upper Saloon Gulch and Spring Creek were connected to the stream network as compared to 70% of the roads in Trumbull.

In June 2002, the Hayman fire burned the study sites in Upper Saloon Gulch. In sites burned at high severity the mean percent ground cover decreased from 90% to 6%, and the soils were strongly water repellent to a depth of 6 or 9 cm. The first two storms of 11 and 17 mm caused extensive rilling and channel incision. Erosion rates averaged 0.75 kg m^{-2} from a 11-mm, 45-minute storm event on 21 July 2002.

At the small watershed scale, the observed high water marks were as much as 1.4 m above the estimated bankfull stage. The Saloon Gulch flume was buried under sediment, while the Brush Creek flume repeatedly clogged with sediment. K, Mg, Ca, Cl, and NO_3 approximately doubled after the fire, while pH remained unchanged.

No sediment was produced from any of the unburned swales in 2002. Thinning operations in fall 2002 doubled the mean percent bare soil from 8% to 16%. However, litter and downed wood still covered 75% of the soil surface, so little or no erosion is expected to occur from typical storm events.

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1. INTRODUCTION

1.1. Background

The Upper South Platte watershed includes over 4,000 km^2 in the Colorado Front Range. It provides 80% of the water for more than 2 million people in the Denver metropolitan area (USDA Forest Service, 2000). The wildfires at Buffalo Creek in 1996 and Hi Meadows in 2000 burned 4690 and 4451 ha, respectively (USDA Forest Service, 2000). Summer storms following the Buffalo Creek wildfire caused severe flooding, erosion, and sediment deposition (Moody and Martin, 2001a). Approximately one-third of the Strontia Springs Reservoir was filled with sediment (Agnew et al., 1997; USDA Forest Service, 2000; Moody and Martin, 2001a). The increase in runoff and erosion after wildfires is a growing major concern in the Colorado Front Range because the increasing forest densities are increasing the risk of large, high-severity wildfires (USDA Forest Service, 2000).

In response to this concern the USDA Forest Service proposed a series of actions to reduce fuel hazards and catastrophic fire risk in the Upper South Platte River watershed (USDA Forest Service, 2000). The proposed actions included mechanical thinning and associated site activities such as prescribed burning and road maintenance (USDA Forest Service, 2000). The presumption was that the increases in runoff and erosion resulting from the proposed actions would be far less severe than the adverse effects resulting from wildfires if no action were taken.

Numerous studies in the Rocky Mountains have shown that forest harvest and thinning increase annual water yields (Brown et al., 1974; Ffolliott, 1975; Leaf, 1975; Hibbert, 1979; Troendle, 1983; Baker, 1986; Troendle and King, 1987; Troendle and Olsen, 1987). This increase is due to the reduction of interception and evapotranspiration loses (Dunne and Leopold, 1978; MacDonald and Stednik, 2003). Paired-watershed experiments in Colorado and northern Arizona have shown that removing 16% to 52% of the forest vegetation increases annual runoff by 24% to 79% (Baker, 1986; Troendle and Olsen, 1987; Troendle and King, 1987; Hibbert and Gottfried, 1987).

Thinning can potentially increase the size and duration of peak flows. In northern Arizona removing 30-50% of the ponderosa pine resulted in an estimated peak flow increase of 20-28% from a 100-year storm event (Ffolliot, 1975). When 77% of the trees had been removed, the estimated peak flow increase from the same storm was 90% (Brown et al., 1974).

An increase in the size or duration of high flows will increase the sediment transport capacity and possibly alter channel morphology by scour or bank erosion (Schumm, 1971; Troendle and Olsen, 1987). Harvesting 26% of the timber from a small, sub-alpine forested basin in Colorado significantly increased sediment yields (Troendle and Olsen, 1987). The increased sediment yields were attributed primarily to in-channel sources initiated by the increase in flow rather than an increase in erosion due to road building and forest harvest. In Arizona thinning ponderosa pine forests did not significantly increase annual sediment yields relative to untreated watersheds (Ffolliott, 1975). In both the Colorado and Arizona studies sediment yields were measured by excavating weir ponds; hillslope-scale erosion rates were not measured. There have been no studies on the effects of thinning on hillslope erosion rates in ponderosa pine forests in the Colorado Front Range.

In addition to altering the amount of runoff, forest management can alter the physical and chemical characteristics of the runoff. Turbidity, total suspended solids, temperature, and nutrients may increase, depending on factors such as the amount of soil disturbance, slope steepness, and the amount and intensity of precipitation (MacDonald and Stednik, 2003). Only a few studies in the Rocky Mountain Region have documented the effects of forest thinning on water quality at the small catchment scale (Brown et al., 1974; Ffolliott, 1975; Troendle and Olsen, 1987). Some studies found that thinning did not have any effect on water quality parameters such as total suspended solids, or the concentrations of calcium, sodium, iron, phosphorus, and nitrate (Brown et al., 1974, Ffolliott, 1975). There is little information on the effects of thinning on water quality in the Colorado Front Range (Brown, et al., 1974; Stednick, 1987; MacDonald and Stednik, 2003).

The forest roads and skid trails associated with forest thinning can alter runoff processes on the hillslope scale (Ffolliott, 1975; Baker, 1987; Hibbert and Gottfried, 1987; Luce and Wemple, 2001). Key changes include the low road surface infiltration rate (Luce and Cundy, 1994; Ziegler et al., 2000) and the interception of subsurface flow (Megahan, 1972). The resulting increase in surface runoff can increase the size of peak flows (La Marche and Lettenmaier, 2001), and possibly change the morphology of first-or second-order streams (Duncan et al., 1987; Wemple et al., 1996; Jones, 2000; Bowling and Lettenmaier, 2001; Fransen et al., 2001; La Marche and Lettenmaier, 2001; Wemple et al., 2001; Lane and Sheridan, 2002). Most paired watershed studies have necessarily evaluated and combined effects of forest management and roads (Megahan and Kidd, 1972; Tague and Band, 2001). Hence it is difficult to separate the effects of forest management on runoff at the catchment scale from the effects of roads (MacDonald and Stednik, 2003).

In addition to increasing surface runoff, forest roads are a chronic source of sediment (Megahan and Kidd, 1972; McCashion and Rice, 1983; Reid and Dune, 1984; MacDonald et al., 1997; Constantini et al., 1999; Luce and Black, 1999; MacDonald et al., 2001; Ziegler et al., 2000). One study in northwestern California estimated that forest roads occupied for less than 4% of the harvested area but contributed 40% of the total erosion (McCashion and Rice, 1983). Sediment production from unpaved forest roads is often predicted by the product of road surface area times slope (Anderson and MacDonald, 1998; Luce and Black, 1999; Luce and Black, 2001b; MacDonald et al., 2001), as the amount of surface runoff is proportional to the road surface area and the amount of energy available for sediment transport is proportional to road slope.

Ground cover and traffic also affect the erosion rates from unpaved forest roads (Luce and Black, 1999; Fransen et al., 2001; MacDonald et al., 2001). On bare road surfaces the impact of raindrops will detach particles (Reid and Dune, 1984; Fransen et al., 2001; Luce and Black, 2001a; Ziegler et al., 2001). Soil texture affects road erosion rates; roads on silty clay loams in the western Cascades of Oregon produced nine times more sediment than roads on gravelly loams (Luce and Black, 1999). In southeast Queensland in Australia, roads on sandy-textured soils produced only 9% as much clay as roads on finer-textured soils (Constantini et al., 1999). An increase in traffic can increase erosion rates (Constantini et al., 1999) by increasing the availability of fine particles, as vehicles will break down larger particles and “pump” finer particles to the surface (Luce and Black, 2001a).

Another important issue is the proportion of sediment that is delivered to the stream network. Sediment from the roads is delivered to streams where the roads intersect the channel network (Duncan et al., 1987; Wemple et al., 1996; MacDonald et al., 2001; La Marche and Lettenmaier, 2001; Lane and Sheridan, 2002). Forest roads also can increase the drainage density by as much as 50%, which will increase the amount of road-derived sediment that is delivered to the stream network (Wemple et al., 1996). However, very little is known about the connectivity of the road network to the stream network in the Colorado Front Range, or the relative contribution of road-derived sediment to the sediment loads in stream and rivers.

The amount of sediment delivered to the stream network also will depend on the particle-size distribution of the eroded sediment. In western Washington more than 50% of the particles smaller than 0.063 mm were delivered to the stream, but only 10% of particles between 0.5 and 2.0 mm (Duncan et al., 1987). In rainfall simulation experiments particles smaller than 0.02 mm comprised only 1-6% of the road surface, but accounted for 50-90% of the sediment in the runoff (Costantini et al., 1999). These examples indicate that smaller particles are selectively eroded and delivered to streams. Relatively few studies have compared the texture of the road surface with the texture of the eroded sediment (Constantini et al., 1999; Luce and Black, 1999), and there are no such data for the Colorado Front Range.

One of the areas planned for thinning in the Upper South Platte River watershed was burned by the Hayman fire in June 2002 (USDA Forest Service, 2003). The burned area included all of the study sites established in upper Saloon Gulch in mid-June 2001. The re-establishment of these sites in July 2002 provided a unique opportunity to monitor the effects of fires on runoff and erosion rates, and compare these data to pre-fire conditions. While a number of studies in the Colorado Front Range have documented the effects of wildfires on runoff and erosion rates (Benavides-Solorios and MacDonald, 2001; Moody and Martin, 2001b; Benavides-Solorio, 2003; Kunze, 2003; Wagenbrenner, 2003), none of these studies had pre-fire data for comparison.

The increase in runoff and erosion rates after wildfires has been attributed to the loss of canopy and ground cover and the formation of a water repellent layer at or near the soil surface (Morris and Moses, 1987; Prosser and Williams, 1998; Johansen et al., 2001; Benavides-Solorios and MacDonald, 2001). The resultant increases in runoff and erosion rates are often transmitted downstream, leading to bank erosion, sediment deposition, and channel scour (Keller et al., 1997; Moody and Martin, 2001b; Elliott and Parker, 2001; Conedera et al., 2003).

An increase in suspended sediment is one of the most important water quality issues following wildfires (Tiedemann et al., 1979). A few studies in the Colorado Front Range have qualitatively or quantitatively documented the effects of wildfires on suspended sediment concentrations (Agnew et al., 1997; Kunze, 2003). Another water quality issue is the increase in nutrient concentrations from ash and sediment (MacDonald, and Stednik, 2003). In northern Portugal concentrations of nitrate, phosphorus, calcium, magnesium, and potassium increased after an understorey wildfire in eucalyptus and pine forests (Thomas et al., 2000). Qualitative changes in water quality were observed after the Buffalo Creek fire (Agnew et al., 1997), but there is little information in the scientific literature for the Colorado Front Range (MacDonald, and Stednik, 2003).

1.2. Goals and Objectives

Given the change in conditions due to the Hayman fire, the goals of this study were to evaluate the effects of both thinning and wildfires on runoff and sediment production at both the hillslope and small catchment scales. At the hillslope scale, the specific objectives were to: (1) compare sediment production rates from thinned, unthinned, and severely-burned swales; (2) measure sediment production rates from unpaved roads; (3) determine the relative effect of key independent variables such as rainfall erosivity, ground cover, and slope on sediment production rates; (4) compare particle-size distributions between source areas and the eroded sediment to determine whether the erosion and transport is size dependent; and (5) assess the connectivity of roads to streams, and whether connectivity can be predicted from factors such as road contributing area, hillslope gradient, distance from the stream, and surface roughness.

At the small catchment scale, the specific objectives were to: (1) measure changes in runoff, sediment yields, and water quality as a result of thinning activities and fires; and (2) determine whether there were any changes in channel morphology as a result of the observed changes at the hillslope scale.

The information from this study should help forest managers assess the likely effects of thinning and wildfires on runoff and erosion rates. The understanding developed from this study should help guide future management activities.

2. METHODS

2.1. Study Area

The Upper South Platte River Basin is southwest of Denver in the Pike-San Isabel National Forest. The Spring Creek, Saloon Gulch, Trumbull, and Brush Creek areas were selected as the primary study sites because they were considered to be representative of the areas to be treated under the Upper South Platte Protection and Restoration Project (USPPRP) (Figure 1).

The climate in the study area is characterized by cold winters and warm summers. In winter the average daily temperature is 1^{o}C, and the average daily minimum temperature is about -12^{o}C. In summer the average daily temperature is 18^{o}C, and the average daily maximum temperature is about 28^{o}C (USDA Forest Service, 1992).

Mean annual precipitation is 41 cm with 70% falling from April through September. Summer precipitation occurs mostly as convective thunderstorms. The 1-year daily rainfall is 3.2 cm, and the 1-year, 30-minute rainfall intensity is 13 mm (Hershfield, 1961). Average seasonal snowfall is about 168 cm or approximately 17 cm snow water equivalent (SWE), and this can fall from late September through May (USDA Forest Service, 1992).

The majority of the project area lies between 2300 and 2750 m above sea level. Ponderosa pine (*Pinus ponderosa*) forests cover approximately 53% of the area in the USPPRP, and these are found mostly at lower elevations. Forests dominated by

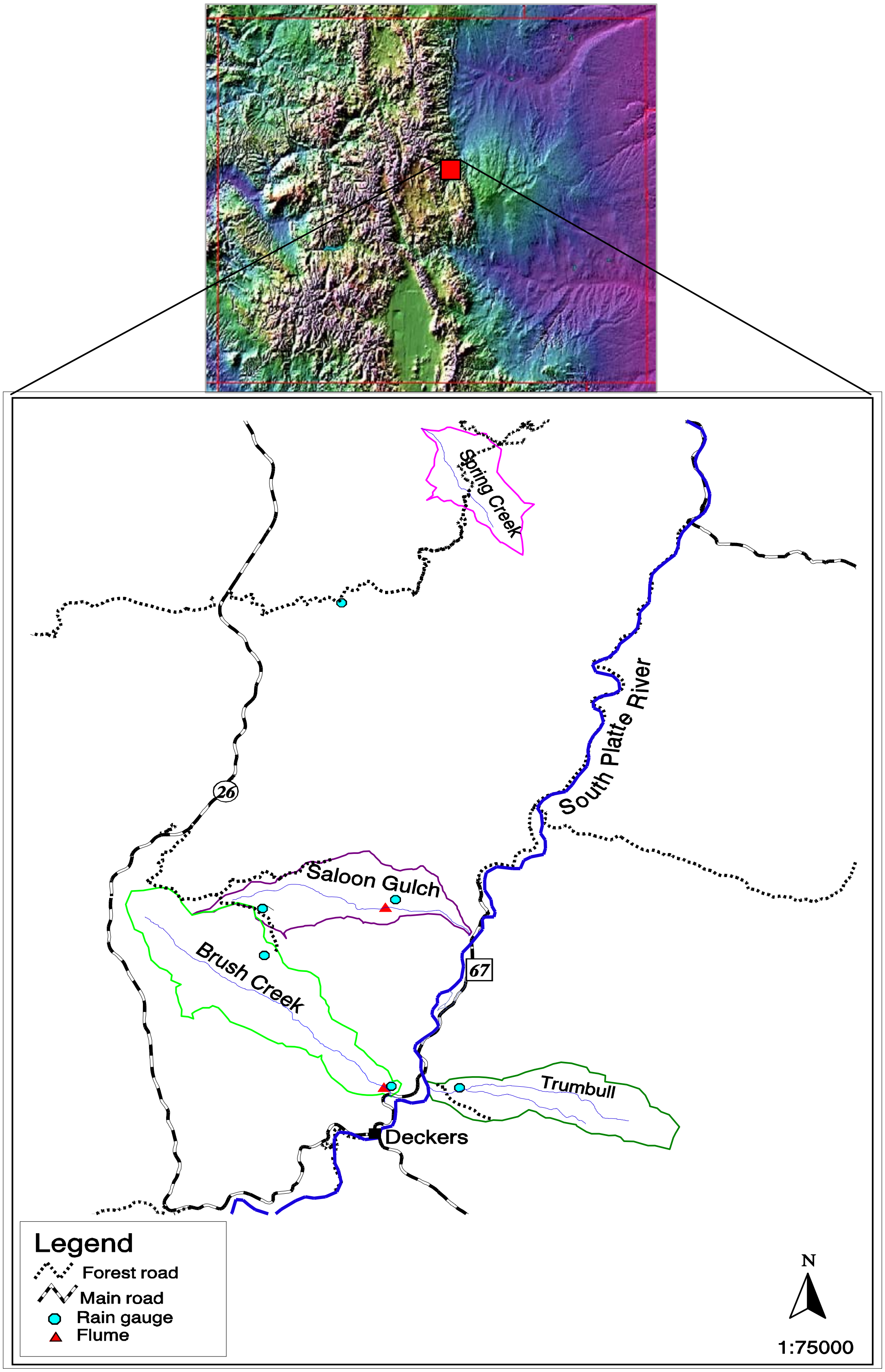


Figure 1. Map of the study sites, including flumes and rain gauges. The solid lines indicate catchment boundaries.

Douglas-fir (*Pseudotsuga menziesii*) account for approximately 37% of the project area, and these are found primarily on north aspects and at higher elevations (USDA Forest Service, 2003). At higher elevations one can also find lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and spruce-fir (*Picea engelmannii-Abies lasiocarpa*) forests. Ground vegetation is mostly Arizona fescue (*Festuca arizonica*) and kinnikinnick (*Arctostaphylos uva-ursi*) (USDA Forest Service, 1992).

The geology of the study areas is dominated by granite and associated igneous rocks of the Pikes Peak batholith (USDA Forest Service, 1992). Within the project area the major soil series are the Kassler and Sphinx series. The Sphinx series is characterized by rapid permeability (15-51 cm hr^{-1}) for both the O_i (0-10 cm) and A (10-30 cm) horizons. For the majority of the soil phases the texture is gravelly coarse sandy loam. Percent organic matter is 1-2% (USDA Forest Service, 1992). This series dominates the Spring Creek area.

The Kassler series is the main soil in the Trumbull area. This series is characterized by moderately rapid permeability (5-15 cm hr^{-1}) for the A_1 horizon (0-15 cm), and rapid permeability (15-51 cm $hour^{-1}$) for the A_2 (15-33 cm) and C (33-150 cm) horizons. The texture is gravelly coarse sandy loam, and percent organic matter varies from 2-4%.

The Saloon Gulch and Brush Creek areas were not included in the soil survey. Field observations and the presence of weathered granite suggest that the soils in these areas are similar to the Kassler and Sphinx soil series.

2.2. Precipitation

Six tipping-bucket rain gauges with a resolution of 0.025 cm (0.01 inch) per tip (Onset Computer Corporation, 2001) were installed in the project area. One rain gauge was installed in Trumbull, one along the road in Spring Creek, and the other four rain gages were installed in the upper and lower portions of Saloon Gulch and Brush Creek, respectively (Figure 1). Table 1 lists the elevation, date of installation, and total precipitation for each gauge for 2001 and 2002. In this study summer precipitation is defined as the period from 1 May to 31 October, as this is when the precipitation falls primarily as rain and all of the sediment-producing storms occur (Benavides-Solorios, 2003). The nearest long-term record is from Cheesman at 39.22^{o} N and 105.28^{o}W, and the data from 1902 to 2002 were used to calculate the mean monthly and mean annual precipitation. The difficulty in measuring the snowfall means that the summer precipitation data are more reliable than the winter or annual data.

Table 1. Location, elevation, starting date, and total precipitation for the six rain gauges used in this study. The numbers in parentheses are the percent of the total precipitation that fell between 1 May and 31 October.

Location	Elevation (m)	Starting date	Precipitation (cm) 2001	Precipitation (cm) 2002
Upper Saloon Gulch	2410	06-Aug-01	8.5 (75)	21.9 (77)
Lower Saloon Gulch	2080	06-Aug-01	5.8 (64)	15.7 (86)
Trumbull	2000	06-Aug-01	8.3 (74)	15.1 (85)
Spring Creek	2280	06-Aug-01	13.8 (73)	18.5 (70)
Upper Brush Creek	2350	28-Sep-01	3.5*	18.4* (60)
Lower Brush Creek	1950	14-Sep-01	2.8 (0)	20.6 (80)

* No data available from 18 October 2001 to 25 January 2002 due to animal interference, and from 16 May to 17 July 2002 due to the Hayman fire.

Rainfall erosivity was calculated for all rainfall events greater than 5 mm following the procedure described by Renard et al. (1997). An event was defined as two or more tips separated from a previous tip by at least one hour.

2.3. Hillslope scale

Sediment fences were used to measure sediment production rates from swales and roads. Twenty paired swales were established in the project area, with 11 pairs in Upper Saloon Gulch, 8 pairs in Trumbull, and one pair in the Spring Creek catchment. In this study swales are defined as zero- or small first-order catchments with only intermittent flow. Smaller swales were selected to minimize the potential for sediment storage and maximize the sensitivity for detecting treatment effects. Slopes were generally less than about 30-40%, as this was the upper limit for the proposed ground-based thinning treatments. One swale of each pair was randomly selected for treatment, and the other was designated as a control. A sediment fence was installed at the base of each swale (Robichaud and Brown, 2002; http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm). Two fences were installed on unusually steep and bare slopes in the Trumbull area.

The sediment fences were constructed of rebar and a geotextile fabric. Pieces of rebar 1.2-m long and 1.3 cm in diameter were driven approximately 50 cm into the ground using a sledgehammer or post pounder. The rebar were more tightly spaced in the middle of the channel and were progressively more widely spaced as they extended upslope. A line level was used to ensure that the center of the fence was lower than the upslope edges of the fence. This design ensured that any surface runoff passed over the top of the fence rather than eroding around the edges. A piece of 1.2-m wide Lumite fabric was attached to the rebar using baling wire, and the extra fabric was spread out in front of the fence to serve as an "apron". Litter and roots were removed from the leading edge of the apron, and the edge of the apron was secured to the mineral soil surface with landscape staples or large rocks to prevent underflow. This apron facilitated the identification and removal of the sediment trapped by the fence. In effect, the sediment fences act as small dams since the permeability of the fabric is low relative to the potential surface inflow. Information on the Lumite fabric and landscape staples can be found at http://www.shawfabrics.com.

Sediment fences were installed in each swale between late June and mid-August 2001. All of the sediment fences in Upper Saloon Gulch were burned by the Hayman fire and the fences were reinstalled in July 2002. In many cases a second fence was added to increase the sediment storage capacity. The materials and person hours required for installing each sediment fence was recorded.

The ground cover in each swale was measured by conducting systematic point counts (Bonham, 1989) along a series of evenly-spaced transects placed perpendicular to the swale axis. The first step was to measure the length of the swale axis with a 100-m tape, and this distance was divided into approximately 10 equal segments. At each segment, the width of the swale was measured and the cover was sampled at a set interval to yield at least 100 sample points per swale. At each sample point the cover was classified as litter, downed wood, live vegetation, rock, or bare. A random number was used to determine the distance to the first sample point along each transect.

The ground cover in each swale was measured at the beginning of the study in summer 2001. In upper Saloon Gulch the ground cover was re-measured after the Hayman fire in July 2002. In Trumbull the ground cover was remeasured before thinning in September 2002 and after thinning in October 2002. Ground cover was not assessed for the two bare hillslopes in Trumbull because the slopes were approximately 70-75% and the disturbance from conducting the cover count could affect the sediment production rate.

The slopes of the swale axis and the adjacent hillslopes were measured with a clinometer. If the axis slope varied substantially, multiple measurements were taken to obtain a distance-weighted mean. The gradient of each sideslope was measured at approximately the middle of the swale, and these values were averaged to yield a mean sideslope gradient.

The area of each swale was calculated from the measured axis and transect lengths. The area of each swale also was measured by walking the perimeter of the contributing area above the sediment fence and logging the UTM coordinates with a GEO Explorer II global positioning system (GPS). This device is accurate to 2-5 m in the x and y directions (GeoExplorer II, 1996). These coordinates were used to identify the swale location and calculate the contributing area. For some of the swales a GPS unit with an accuracy of about 10 m was used.

Soil water repellency was measured in each swale using the critical surface tension (CST) method (Huffman et al., 2001). Three soil pits were randomly selected going up the swale in a zigzag pattern. The location of each soil pit was classified as under the tree canopy or in an intercanopy area. CST measurements were made at the mineral soil surface (“0 cm”) and at 3, 6, 9, and 12 cm depths in the upper, middle, and lower portion of each swale. At least 5 drops were applied at each depth starting with deionized water. Solutions with progressively higher ethanol concentrations were used if all 5 drops were not absorbed into the soil within 5 seconds. The solutions used had 0, 1, 3, 5, 9, 14, 19, 24, 34, 48, 60, 72, and 80% ethanol. Higher ethanol concentrations have lower surface tensions and indicate stronger soil water repellency. Soil water repellency was measured after the Hayman fire in early August 2002 in Upper Saloon Gulch and in mid-August 2002 in Trumbull.

Crest gages were installed above the sediment fences in the axes of all the paired swales in Upper Saloon Gulch, Trumbull, and Spring Creek (MacDonald, 2002). The crest gages were attached to rebar and placed on perforated bricks set in the middle of the channel. The top of the brick was leveled with the channel bottom. The height of the cork powder on the graded rod inside the gage was recorded after each storm.

Soil samples from 0-3 cm were taken from each of the swales in Trumbull and Upper Saloon Gulch. The swales were divided into upper, lower, and axis locations. Ten cores each were taken in the upper and lower portions of the swale in a zigzag pattern, and 10 cores were taken along the swale axis. The 10 cores from each location were combined to yield three composite samples from each swale.

The particle-size distribution of these composite samples was determined following Gee and Bauder (1986). Approximately 100 g of soil were mechanically sieved for 10 minutes. The sieved fractions were divided into coarse gravel (>12.5 mm), fine gravel (2-12.5 mm), very coarse sand (1-2 mm), coarse sand (0.5-1.0 mm), medium sand (0.25-0.50 mm), fine sand (0.125-0.25 mm), and very fine sand (0.053-

0.125 mm). Percent silt and clay was determined by the hydrometer method (Gee and Bauder, 1986) using the sieved fractions smaller than 2.0 mm. These were combined in a beaker and treated with approximately 40-45 mL hydrogen peroxide (H_2O_2) to remove the organic matter. After the reaction was complete, the excess H_2O_2 was removed by gently heating the sample. The contents of the beaker were mixed with 100 mL hexametaphosphate $[KNa(PO_3)]_6$ and 500-600 mL of water, then transferred to a blender and mixed for 3 minutes. This mixture was transferred to a graduated cylinder and water added to make 1000 mL. The sample was vigorously mixed and hydrometer readings were taken at 30, 40, 60, and 90 seconds, as well as at 3, 120, 480, and 1440 minutes.

The sediment collected after storms was manually removed in 20-liter buckets and weighed with a hanging scale to the nearest ¼ kilogram. After weighing the sediment was placed on a tarp and mixed. Two 1-2 kg samples of this sediment were taken and placed in sealed plastic bags. Approximately 250-350 grams of sediment was removed from each bag, weighed, dried at 105^{o}C for 24 hours, and weighed again to determine percent moisture (Gee and Bauder, 1986). The mean percent moisture was used to convert the field-measured wet weight to a dry mass.

The particle-size distribution of the eroded sediment was determined following the same procedure as the soil samples taken from each swale. The mean particle-size distribution of the eroded sediment from a set of sites was calculated from the mass-weighted particle-size distributions.

2.4. Roads

A detailed road survey was conducted along the roads in Upper Saloon Gulch, Spring Creek, and Trumbull. Each road was divided into segments according to the presence of drainage divides and distinct drainage locations. Drainage locations were classified as a culvert, waterbar or dip, pushout, or dispersed runoff. A pushout is where the grader has pushed away the downslope berm to facilitate drainage but did not build a waterbar. Each segment was classified according to the drainage pattern of the road surface (i.e., insloped, outsloped, outslope bermed, planar, planar bermed on both sides, or crowned), and whether there was an inside ditch. The UTM coordinates for the beginning and end of each road segment were determined using the GEO Explorer II.

The data collected for each road segment included segment length, mean gradient, sideslope gradients, active width as evidenced by wheel tracks and the lack of vegetation, total width as defined by the road prism, and cutslope height. Segments were also classified by the position on the hillslope using three categories: ridgetop (<100 m to the ridge), midslope, and valley bottom (<100 m to streams or ephemeral channels). At each drainage point, the presence of a rill or a sediment plume was assessed. If a rill or sediment plume was present, the length and average gradient were measured. For sediment plumes the roughness along its path was categorized as high, medium, or low according to the size and density of the vegetation, woody debris, and rocks. Rill width and depth were measured at three points along the rill: an upper location, which was immediately below the lower edge of the road prism; a middle location; and a lower location, which was close to the rill end but where the rill was still a distinct feature. Rill widths and depths were multiplied to provide an index of the rill cross-sectional area at the upper, middle and lower locations, respectively. A mean cross-sectional area also was calculated for each rill. Multiplying the mean area times rill length yielded a rough index of rill volume.

The rill and sediment plume data were used to classify each road segment into one of four connectivity classes. The four classes were: (1) no sign of concentrated flow below the drainage outlet; (2) concentrated flow was present but extended for less than 20 m; (3) concentrated flow extended for more than 20 m but stopped more than 10 m from the bankfull edge of a stream; and (4) there was a continuous rill or sediment plume to within 10 m of an ephemeral or perennial stream channel.

Sediment fences were installed to measure sediment production from selected road segments in the Trumbull, Upper Saloon Gulch, and Spring Creek areas. Sediment fences were installed wherever the drainage was sufficiently concentrated and there was sufficient gradient to collect the sediment from a culvert, rolling dip, or other drainage location. The design and installation of the sediment fences followed the procedure described for the paired swales. The materials used and person hours needed to install each fence were recorded.

Sediment fences were installed on 17 road segments between late June and early July 2001. Nine sites were on the Spring Creek road, 5 sites on roads in upper Saloon Gulch, and 3 sites in Trumbull. The unequal number of fences in each area is due to the limited number of suitable locations. Three additional fences (3/13, 3/14, and 3/15) were installed in Spring Creek area in summer 2002. In June 2002 the road in Trumbull was regraded and the three fences installed in 2001 were no longer effective in capturing road-related sediment. Four new fences were installed in 2002 after the regarding, but only two were designed to measure segment-scale sediment production.

The Hayman fire compromised three of the road fences in Upper Saloon Gulch because the areas above the road were burned. These sites were discontinued because the resulting overland flow meant that the captured sediment was not solely from the road segment. After each storm or closely-spaced set of storms the sediment from each fence was collected and analyzed in the same way as the sediment collected from the sediment fences in the swales.

Ground cover was measured at a minimum of 100 sample points in summer 2001 and summer 2002 for the active area of each road segment that drained into a sediment fence. The sample points were located along 10 equally-spaced transects across the road segment. The distances between transects and sampling points were determined systematically, while the distance from the start of the segment to the first transect and from the road edge to the first sample point along the transect were determined randomly.

Soil samples from 0-2 cm were taken from each of the road segments with a sediment fence. Ten cores were taken from the upper, middle, and lower portions of the active road surface. Each set of ten cores was composited to yield one sample each for the upper, middle, and lower portions of each road segment. The particle-size distribution of these samples was determined following the same procedure described earlier.

Traffic counters were installed on 21 September 2001 for the Trumbull road and on 28 September for the Upper Saloon Gulch and Spring Creek roads. The traffic counters were placed immediately behind the locked gates that control the access to each of these roads. In mid-July 2002 traffic counters were installed at the end of the Trumbull and Spring Creek roads to determine how many vehicles were traveling to the end of the road where the majority of the sediment fences were located.

2.5. Small-catchment scale

2.5.1. Channel morphology

Channel surveys were conducted on 6 August 2001 for No Name Creek in Trumbull, 15 August 2001 for Brush Creek, and 1 November 2001 for Saloon Gulch. These surveys originated from permanent cross-sections established by the Forest Service in October 1999. At each of these sites, the channel cross-section was surveyed using an engineer's level, stadia rod, and measuring tape. Upstream of each cross-section a 300-m study reach was established following the procedure developed in Harrelson et al. (1994).

In Brush Creek and Saloon Gulch, 76-cm H-flumes were installed to measure discharge on 30 May and 18 June 2002, respectively. The stage record on Brush Creek flume began on 30 May 2002, but the high flow events after the Hayman fire repeatedly clogged the flume and stilling well with sediment, ash, and organic debris. Efforts to keep the flume clear were unsuccessful, so there are no valid flow data after 6 July 2002. The stage recorder and flume in Saloon Gulch, were completely buried by sediment on 21 July 2002, and efforts to collect discharge data were abandoned.

The rebar marking the cross-section in Brush Creek were lost in July 2002 due to the high flows following the Hayman fire. The cross-section was re-established at approximately the same location on 18 July 2002. Two additional cross-sections were established in Brush Creek in summer 2002 to help assess channel changes after the Hayman wildfire. The first of these cross-sections was established on 7 July 2002 immediately upstream of the flume, and the second cross-section was established approximately 100 m further upstream on 2 August 2002. Similarly, two new cross-sections were established in Saloon Gulch on 18 July 2002. The first was approximately one meter downstream of the flume, and the second was 50 m upstream from the first one. The cross-sections in Brush Creek and Saloon Gulch were surveyed after each major storm and at the end of the summer storm season on 20 September 2002.

The particle-size distribution of the bed material was measured by sampling approximately 300 points within the reach following the zig-zag procedure developed by Bevenger and King (1995). The percent of eroding banks was determined by measuring the length of actively eroding banks within the reach.

2.5.2. Runoff and water quality

At No Name Creek in Trumbull, discharge was measured at the upper end of the survey reach due to the lack of flow at the downstream cross-section. Velocity was measured with a Pygmy current meter. In Saloon Gulch discharge was measured by averaging three measurements of the time needed to fill a 1.0-liter bottle.

After the Hayman fire peak discharges in Brush Creek and Saloon Gulch were estimated from cross-section surveys and the high water marks using Manning's equation. Manning's n was calculated from the D_{84} using the equation developed by Lamerinos (1970).

Grab samples were collected 1-2 times per month from August 2001 to December 2002 in Spring Creek, No Name Creek, Saloon Gulch and Brush Creek. These samples were analyzed for sodium, ammonia, potassium, magnesium, calcium, fluoride, chloride, nitrate, phosphorous, sulfate, total suspended solids, and turbidity at the USDA Forest Service Rocky Mountain Forest and Range Experiment Station in Fort Collins (Musselmann and Elsworth, 2001). Water temperature, pH, and conductivity were measured in the field

2.6. Data Analysis

Simple linear regression was used to compare swale areas determined from the transects and the swale areas calculated from the GPS data. The General Linear Model (GLM) procedure in SAS (Cody and Smith, 1991) was used to test for differences in the mean soil water repellency at each depth between upper Saloon Gulch and Trumbull. Sites, depths and position in the swale (upper, lower, and channel) were treated as categorical variables.

The predictability of sediment production from the swales was tested using stepwise multiple regression. The independent variables were swale contributing area, axis gradient, sideslope gradient, area times axis slope gradient, and area times sideslope gradient. Swale sediment production, area times axis slope gradient, and area times sideslope gradient were log transformed because the variability increased with increasing values (Ott and Longnecker, 2001).

Road segment length, width, area, slope, and area times slope were treated as independent variables. Analysis of covariance was used to determine if these independent variables were collinearly related. Stepwise multiple regression was used to determine whether sediment production from the road segments could be predicted from the various road segment characteristics. Mallow's Cp was used to protect against higher R^2 resulting from having too many independent variables in the model (Ott and Longnecker, 2001). Independent variables were kept in the model when $p \leq 0.05$. Models with the lowest Mallow's Cp and the highest R^2 were selected.

Multiple regression was used to assess the relationship between sediment plume length and road segment characteristics. Sediment plume length and active road area times slope were log transformed because the variability increased with increasing values. Roughness and connectivity classes were each treated as categorical variables. The relationship between active area times slope and sediment plume length was analyzed for each connectivity class since connectivity class was a significant control on sediment plume length.

The relationship between rill volume and road segment characteristics was tested using multiple regression. Roughness and connectivity classes were treated as categorical variables. The rill volume data were combined across roughness and connectivity classes since these variables were not significant at $p \leq 0.05$. The relationship between rill cross-sectional area and rill cross-sectional position (upper, middle, lower) was tested using a general linear model. Roughness and connectivity classes were treated as categorical variables.

The differences in ground cover in 2001 between the swales in Upper Saloon Gulch, Trumbull, and Spring Creek were tested using a general linear model. A paired t-test was used to test for differences in each ground cover category before and after the Hayman fire for the swales in upper Saloon Gulch, and before and after thinning for the swales in Trumbull.

Differences in water quality before and after the Hayman fire were tested using a paired t-test. The relationship between suspended solids and turbidity was tested using simple linear regression.

ANOVA was used to test for differences in particle-size between the upper, lower, and middle portions of the swales in both Trumbull and upper Saloon Gulch. The data from the upper, middle, and lower parts of the swales were combined since there were no significant differences in the particle-size distributions with swale location. A two-sample t-test was used to test for differences in the surface soils between upper Saloon Gulch and Trumbull. A paired t-test was used to test for differences in the proportions of different particle-size classes between the surface soils in the swales and the eroded sediment.

Similarly, a paired t-test was used to test for differences in the proportions of different particle-size classes between the road surface and the eroded sediment for upper Saloon Gulch, Spring Creek, and Trumbull. A general linear model was used to test for differences in the proportions of different particle-size classes for the eroded sediment from different storms.

3. RESULTS

3.1. Precipitation

Precipitation during the summer rainy season varied greatly between sites in both 2001 and 2002. From 8 August to 31 October 2001 Spring Creek received 13.8 cm of precipitation as compared to just 6.4 cm at both upper Saloon Gulch and Trumbull (Figure 2). Lower Saloon Gulch, upper Brush Creek, and lower Brush Creek each recorded less than 0.5 cm of precipitation (Figure 2).

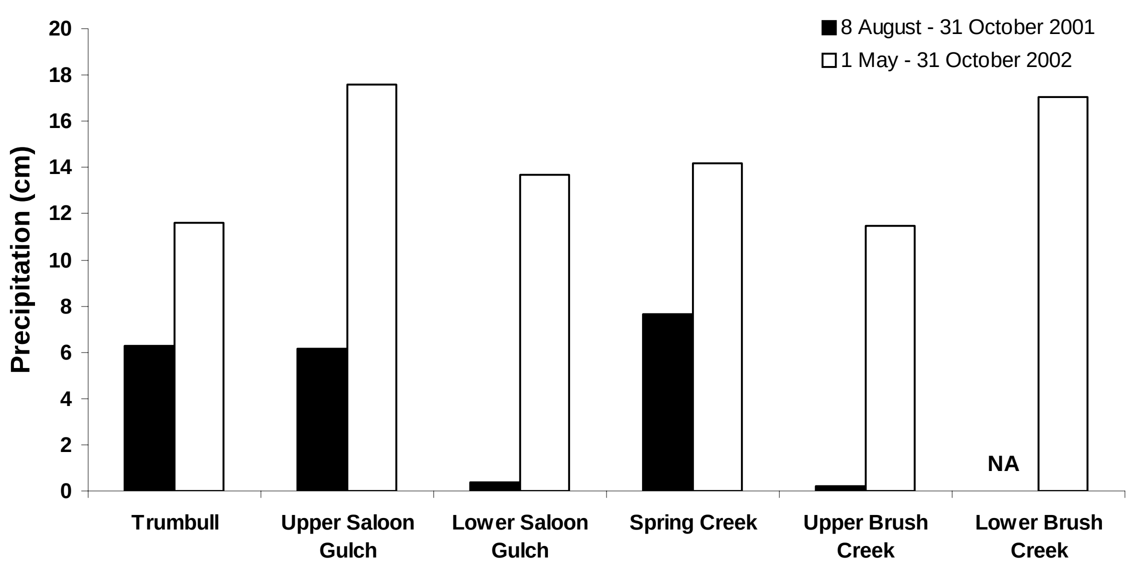


Figure 2. Total precipitation for the different rain gauges from 8 August-31 October 2001 and 1 May-31 October 2002. NA indicates not available.

In 2002 the mean summer precipitation in the study area was 14.3 cm. Within the study area values ranged from 11.7 cm at Trumbull to over 17 cm at lower Brush Creek and upper Saloon Gulch (Figure 2).At Cheesman summer precipitation in 2002 was 17.2 cm, or 40% of the historic mean. This indicates that summer 2002 was very dry.

Most of the rainfall from mid-May to late September resulted from short-duration summer convective storms (Appendix 2). Most of the rain events within this period were clustered in 2-5 day periods. From 8 August to 31 October 2001, the mean number of rain events was 16 and the range was from 10 to 24. The mean daily rainfall on the days with rain was only 2.3 mm, and only 34% of the days with rain had at least 5 millimeters. Only four of the daily rainfall totals in 2001 and in 2002 had 16 or more millimeters of rain (Figure 3). The largest daily rainfall was 27.3 mm on 13 August 2001 in Spring Creek, and this is substantially less than the estimated 1-year, 24-hour rainfall of 33 mm (Hershfeld, 1961). This same storm produced only 7.1 mm and 10.0 mm of rainfall at upper Saloon Gulch and Trumbull, respectively, indicating the high spatial variability of summer rainfall events within the study area.

From 1 May to the beginning the Hayman fire on 8 June 2002, the different study sites received from 22 to 38 mm of rain. The largest storm was 11.0 mm on Spring Creek and only 2-3 rain events generated 5 or more millimeters of precipitation (Appendix 2).

Following the Hayman fire the study sites received from 93 to 124 mm of rain in 28 to 39 storms. Fifty-five percent of the days with rain had 5 or more millimeters of rain. The largest storm event was 30.1 mm on 21 July 2002 in lower Saloon Gulch.

This storm produced 11.2 mm of rain in upper Saloon Gulch and only 2.3 mm of rain in Spring Creek (Figure 4a). The second-largest storm was on 6 July 2002 and the amount of rain varied from 9.7 mm at Trumbull to 20.0 mm in Spring Creek (Figure 4b). These data again illustrate the spatial variability of summer rainfall events.

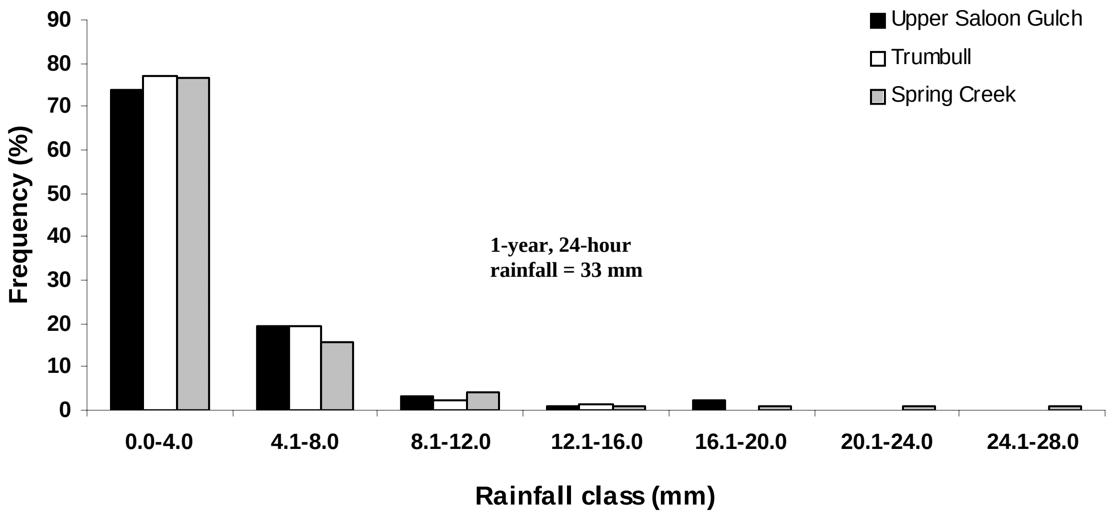
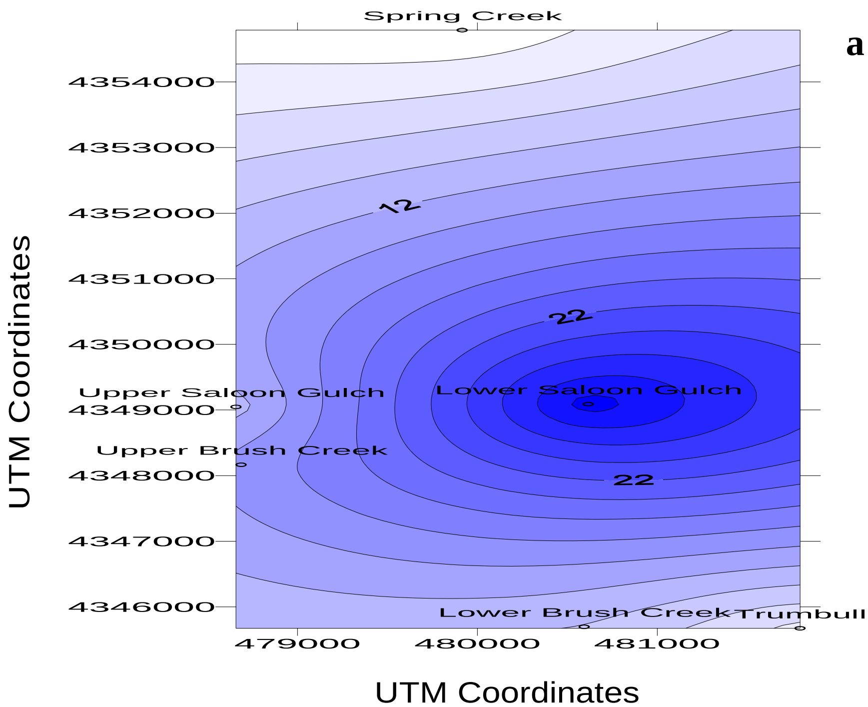


Figure 3. Frequency distribution of the daily rainfall for days with rain in upper Saloon Gulch, Trumbull, and Spring Creek from 8 August-31 October 2001 and 1 May-31 October 2002.



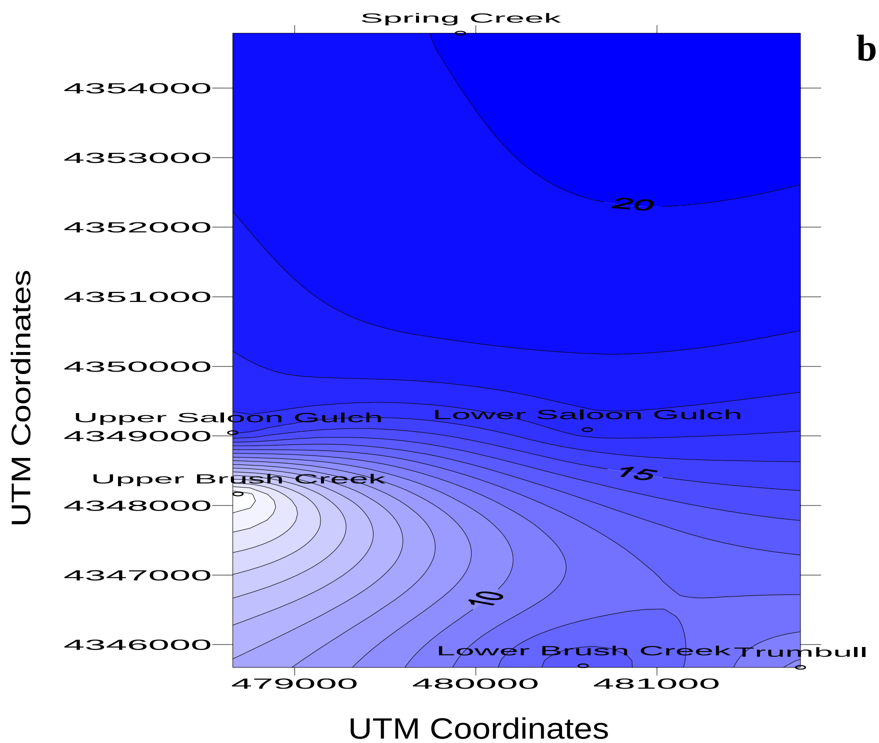


Figure 4. Spatial distribution of rainfall in millimeters for the storms on: (a) 21 July 2002, and (b) 6 July 2002.

Approximately 85% of the storms in 2001 and 2002 had a maximum 30-minute rainfall intensity of less than 20 mm hr^{-1}. Only two storms had values of at least 60 mm hr^{-1} (Figure 5). The maximum 30-minute rainfall intensity was highly variable across sites and between storms for both the 2001 and 2002 summer seasons (Appendix 2). At Spring Creek the two largest storms in 2001 had maximum 30-minute rainfall intensities of 28.3 and 46.5 mm hr^{-1}. Other than Spring Creek, the maximum 30-minute rainfall intensity in summer 2001 was 14.0 mm hr^{-1} for a 8.6 mm storm at lower Saloon Gulch, and this is slightly more than the estimated 1-year, 30-minute precipitation of 11-12 mm (Hershfeld, 1961).

In summer 2002 the highest 30-minute rainfall intensities were 62.0 and 69.4 mm hr^{-1} for the storm on 21 July 2002 from upper and lower Saloon Gulch, respectively. The maximum 30-minute intensities for the same storm at upper and lower Brush Creek were 38.5 and 32.0 mm hr^{-1}, respectively.

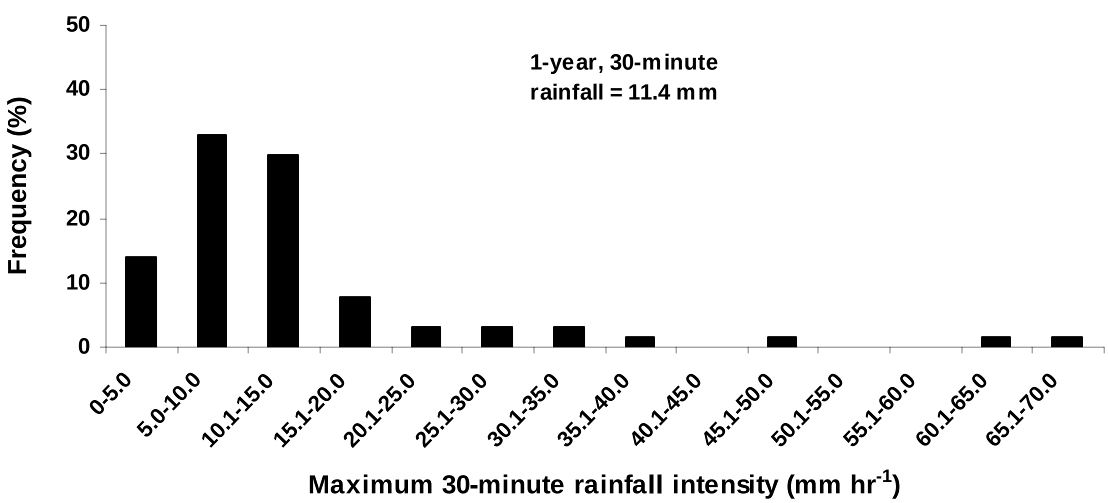


Figure 5. Frequency distribution of the maximum 30-minute rainfall intensities for the 6 rain gauges from 8 August-31 October 2001 and 1 May-31 October 2002.

Rainfall erosivities also were highly variable across sites and between storms (Appendix 2). In 2001 the calculated erosivities varied from 38 MJ mm ha^{-1} yr^{-1} at lower Saloon Gulch to 572 MJ mm ha^{-1} yr^{-1} at Spring Creek (Figure 6). For comparison, the mean annual erosivity is approximately 340 MJ mm ha^{-1} yr^{-1} (Renard et al., 1997).

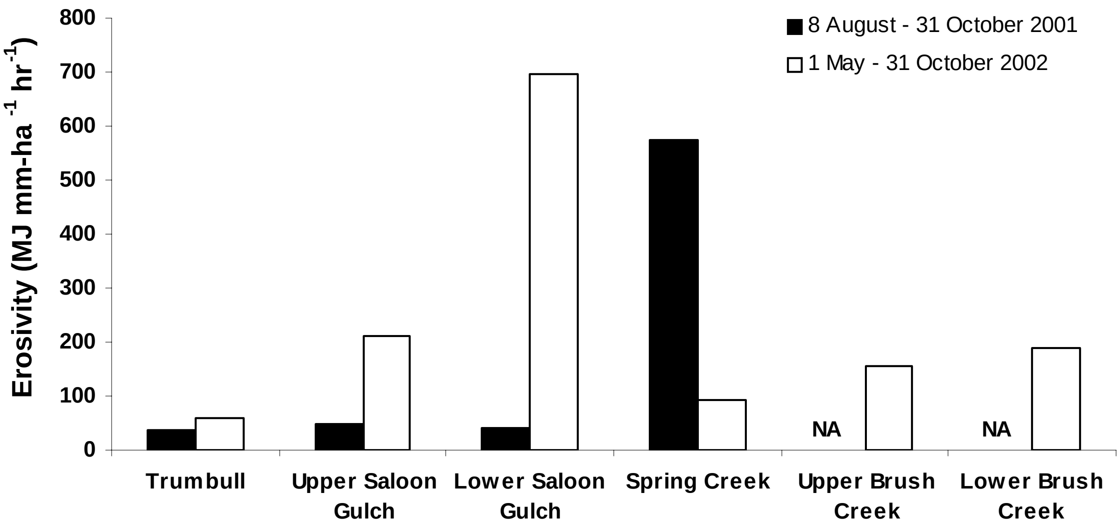


Figure 6. Total erosivity for the different rain gauges from 8 August-31 October 2001 and 1 May-31 October 2002. NA indicates not available.

Approximately 97% of the rainstorms in 2001 and in 2002 had an erosivity of less than 135 MJ mm ha^{-1} hr^{-1}. Spring Creek generally had the highest rainfall erosivities, and in 2001 the two most erosive storms were on 13 and 21 August. The calculated erosivities at Spring Creek for these storms were 350 MJ mm ha^{-1} hr^{-1} and 76 MJ mm ha^{-1} hr^{-1}, respectively.

In 2002 total erosivity varied from 57 MJ mm ha^{-1} yr^{-1}at Trumbull to 696 MJ mm ha^{-1} yr^{-1} at lower Saloon Gulch (Figure 6). The majority of the storms had rainfall erosivities of less than 50 MJ mm ha^{-1} hr^{-1} (Figure 7; Appendix 2). The storm on 21 July 2002 had the highest erosivities, but values varied from 540 MJ mm ha^{-1} hr^{-1} at lower Saloon Gulch to 136 MJ mm ha^{-1} hr^{-1}at upper Saloon Gulch, 107 MJ mm ha^{-1} hr^{-1}at upper Brush Creek, and only 16.2 MJ mm ha^{-1} hr^{-1} in Trumbull.

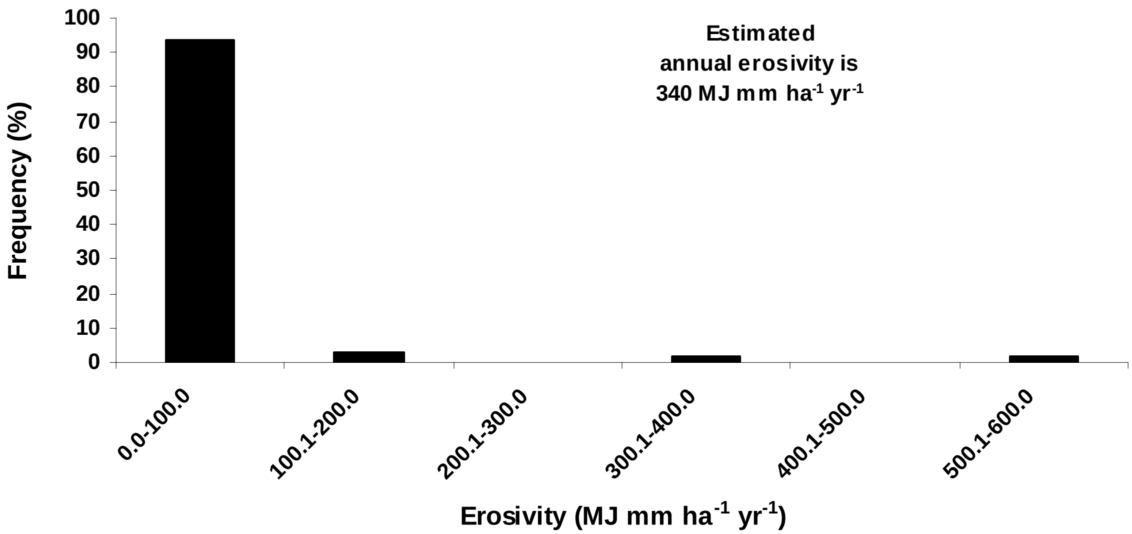


Figure 7. Frequency distribution of storm erosivity for the 6 rain gauges from 8 August-31 October 2001 and 1 May-31 October 2002.

3.2. Paired Swales

3.2.1. General characteristics

The mean contributing area of the swales used in this study was 2700 m^2 (Table 2), and the contributing area for individual swales ranged from 340 to 9800 m^2 (Table 3).

In Trumbull the mean contributing area of the swales was only 940 m^2 (Table 2), as the terrain in this area is highly dissected. The two swales in Spring Creek were larger than average because the terrain is flatter and less dissected (Table 2).

The mean percent difference in contributing areas between the control and treated swales was 24%, and the biggest difference within a pair was 57% (Table 3). There

Table 2. Number of swales, mean contributing area, and mean slopes for the treated and control swales. Standard deviations are in parentheses.

Site		Number of swales	Area (m^2)	Slope (%)	
				Axis	Side
Upper Saloon Gulch					
	Mean of control swales	11	3300 (1870)	23 (5)	19 (5)
	Mean of treated swales	11	4400 (3300)	21 (6)	20 (7)
	Grand mean	**22**	**3900**	**22**	**20**
Trumbull					
	Mean of control swales	8	930 (380)	25 (6)	28 (7)
	Mean of treated swales	8	950 (470)	20 (7)	24 (10)
	Grand mean	**16**	**940**	**23**	**26**
Spring Creek					
	Control swale	1	6100	16	19
	Treated swale	1	6900	15	20
	Mean	**1**	**6500**	**16**	**20**

was very little difference between the mean areas of the treated and control swales in Trumbull, while in upper Saloon Gulch the mean area of the treated swales was 25% greater than the mean area of the control swales (Table 2).

The contributing areas determined from the transects were similar to the areas calculated from the GPS until the contributing area exceeded about 4000 m^2 (Figure

8). The larger differences for the larger swales may be partly due to the difficulty of accurately determining the contributing area, as the larger swales extended onto the flatter ridgetops. The larger swales also had proportionally fewer transects for determining the contributing area, and this would reduce the accuracy of the calculated areas. The contributing areas from the transects were used for calculating erosion rates since one of the two GPS units was only accurate to about 10 m.

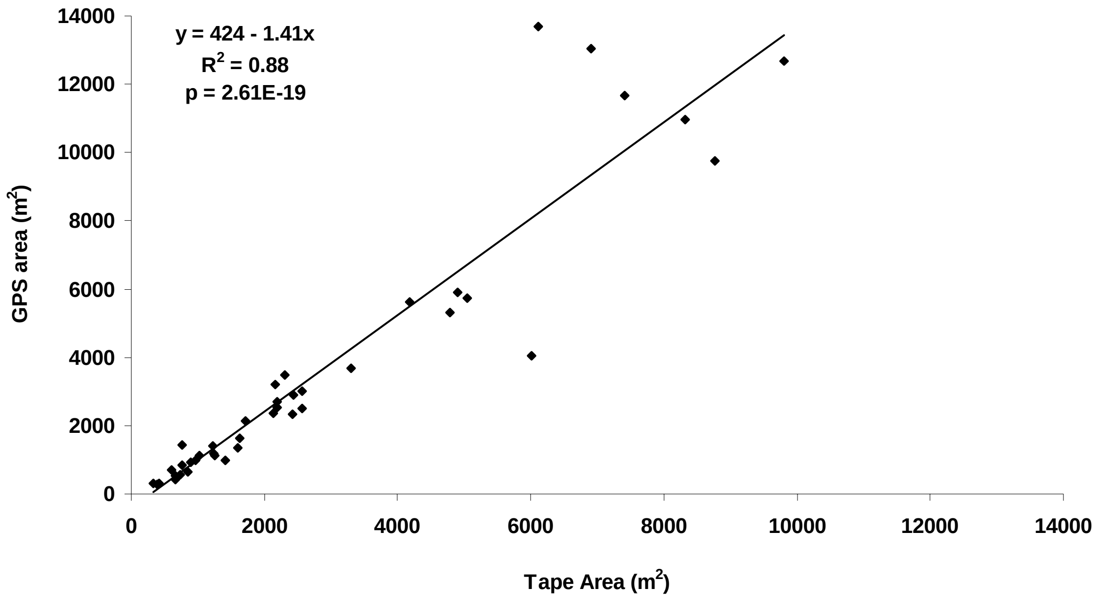


Figure 8. Comparison of the contributing areas as measured from transects versus the GPS data.

Table 3. Contributing area, axis and side slopes, percent ground cover, and sediment production rates for the swales in Spring Creek, Trumbull, and upper Saloon Gulch. C indicates control.

Site	Sediment fence no.	Area (m^2)	Slope (%)		Percent cover				Sediment produced (kg m^{-2})	
			Axis	Side	Bare soil*	Litter and downed wood	Live vegetation	Rock	2001	2002
USG	1\8	8700	15	24	97	3	0	0	0	0.8
	1\9 C	7400	13	13	97	0	3	0	0	0.6
	1\12 C	2400	26	19	94	4	2	< 1	0	0.5
	1\13	2200	24	16	92	7	1	< 1	0	0.6
	1\14	2600	24	16	93	7	0	< 1	0	0.7
	1\15 C	3300	20	23	88	8	4	< 1	0	0.3
	1\16	2600	26	24	94	4	0	2	0	0.6
	1\17 C	1700	26	21	91	8	0	1	0	0.7
	1\18 C	2100	26	19	92	8	0	0	0	0.9
	1\19	1000	30	12	94	4	0	2	0	1.1
	1\20	4800	18	34	89	11	0	0	0	0.8
	1\21 C	4900	19	30	85	10	2	3	0	0.8
	1\22 C	4200	19	24	97	3	0	0	0	0.7
	1\23	9800	21	24	95	5	0	0	0	0.5
	1\24 C	800	32	19	100	0	0	0	0	1.2
	1\25	600	29	16	97	3	0	0	0	1.0
	1\26 C	5000	27	18	80	7	1	12	0	0.5
	1\27	6000	22	22	96	3	0	0	0	0.4
	1\28	2200	20	16	98	2	0	0	0	0.7
	1\29 C	2200	20	16	99	1	0	< 1	0	0.8

Table 3 (continued).

Site	Sediment fence no.	Area (m^2)	Slope (%)		Percent cover				Sediment ($kg\ m^{-2}$)	
			Axis	Side	Bare soil*	Litter and downed wood	Live vegetation	Rock	2001	2002
TRM	2\1	762	36	28	60	37	3	0	0	0
	2\2 C	1000	32	31	34	56	9	1	1.1	0
	2\3	1200	29	36	35	60	4	1	0.6	0
	2\4 C	890	35	30	21	71	8	0	0	0
	2\5	1600	35	30	43	47	9	1	0.3	0
	2\6	2400	20	25	6	76	18	0	0	0
	2\10	NA	76	NA	NA	NA	NA	NA	17	0
	2\11 C	660	25	26	33	62	4	1	0	0
	2\12 C	660	24	36	9	73	18	0	0	0
	2\13	390	30	31	17	71	12	0	0	0
	2\14 C	1600	19	30	4	83	13	0	0	0
	2\15	1400	25	32	5	81	14	0	0	0
	2\16 C	740	24	21	19	67	14	0	0	0
	2\17	340	25	13	6	90	4	0	0	0
	2\19	850	27	9	12	72	15	1	0	0
	2\20 C	420	29	13	26	69	4	1	0	0
	2\21	1200	15	21	12	75	13	0	0	0
	2\22 C	1250	18	28	10	76	14	0	0	0
	2\23	NA	73	NA	NA	NA	NA	NA	13	0
SC	3\1	6100	16	19	5	75	19	1	0	0
	3\3	6900	15	20	10	60	23	7	0	0

* Ground cover in 2002 at USG is after the Hayman fire; percent bare soil includes ash.
NA indicates no measurements were made to minimize site disturbance.

The mean axis and side slopes for all the swales were approximately 23% (Table 2). On average, the swales in Trumbull were slightly steeper than the swales in upper Saloon Gulch, while the two swales in Spring Creek were flatter than most of the other swales. Slope differences between the control and treated swales were generally small (Table 2). The largest mean difference was in Trumbull, where the mean axis slope for the control swales was 25% versus 20% for the treated swales. The contributing areas above the two planar hillslopes in Trumbull had a slope of about 75%, while the steepest paired swales had axis and side slopes of 30-36% (Table 3).

3.2.2. Ground cover

In October 2001 the mean percent ground cover was 85% for the swales in Trumbull, upper Saloon Gulch, and Spring Creek (Figure 9). On average, litter and downed wood covered from 63% to 68% of the ground surface. For individual swales, the percent of litter and downed wood ranged from 35% to 88% (Table 3).

Percent live vegetation averaged 21% for the swales in upper Saloon Gulch, 25% for the swales in Spring Creek, and only 10% for the swales in Trumbull (Figure 9). The lowest value for a single swale was 1% and the highest value was 33% (Table 3). The percent live vegetation on the ground surface in the Trumbull swales was significantly less ($p<0.001$) than in upper Saloon Gulch and Spring Creek.

The mean percent bare soil for all sites was 14%, but values for individual swales ranged from 1% to 60%. On average, the swales in Trumbull had 21% bare soil, or roughly twice as much bare soil as the swales in upper Saloon Gulch and Spring Creek (Figure 9). This difference was significant at $p=0.04$. The greater amount of bare soil in the Trumbull swales is consistent with smaller amount of live vegetation, and is probably due to their lower elevation, preponderance of south-facing slopes, and possibly less precipitation.

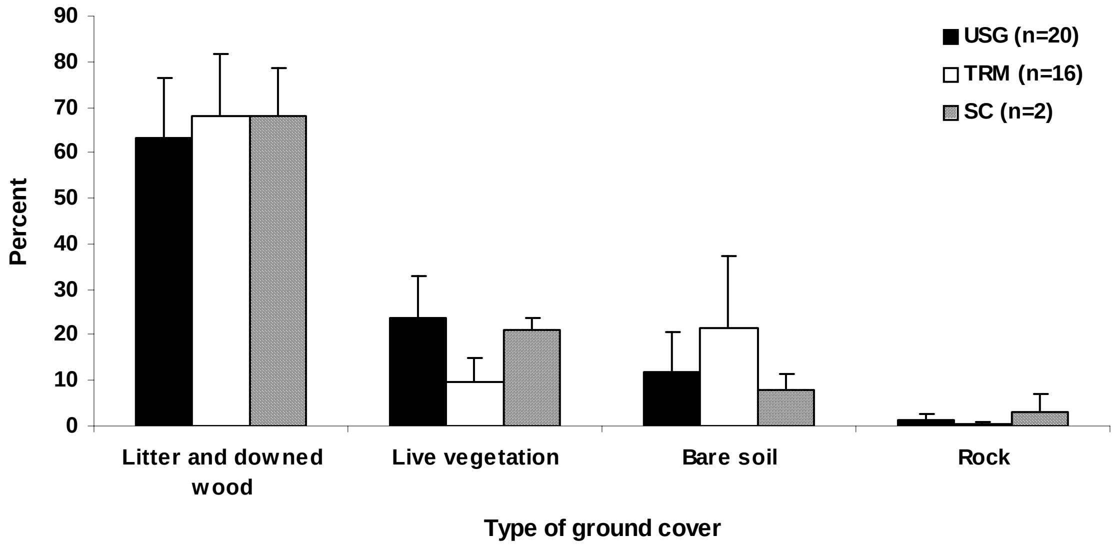


Figure 9. Mean percent cover in upper Saloon Gulch, Trumbull, and Spring Creek in October 2001. Bars represent one standard deviation.

On average, rocks larger than 2 mm provided only 1-4% of the total cover. Values for individual swales were usually less than 3%, although one swale in upper Saloon Gulch and one swale in Spring Creek had 12% rock cover (Table 3).

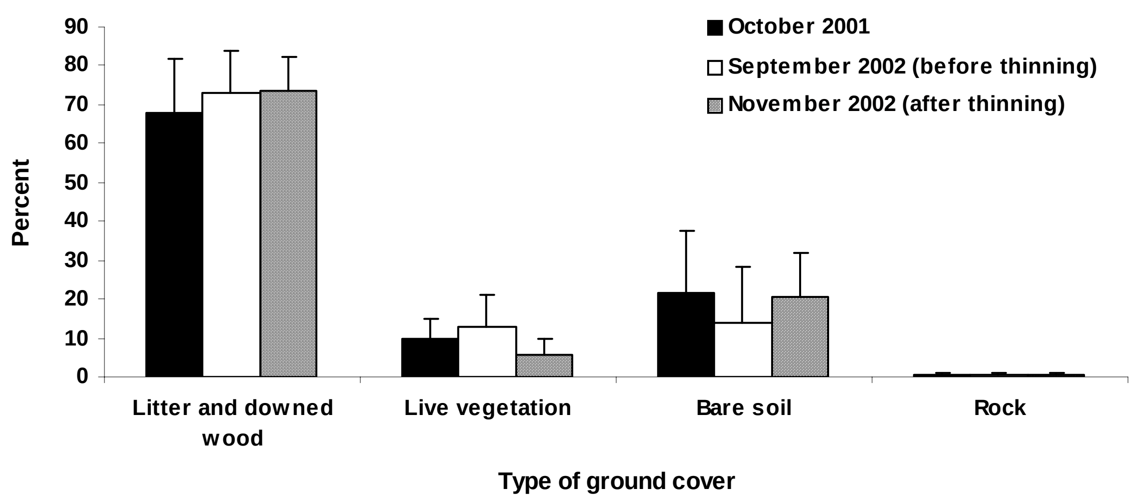


Figure 10. Mean percent cover in Trumbull in October 2001, September 2002 before thinning, and October 2002 after thinning. Bars represent one standard deviation.

There were small differences in the type of ground cover between the treated and the control swales prior to treatment. For all sites, the treated swales had 65% litter and downed wood versus 68% in the control swales. The average difference in percent bare soil was 3%, and the biggest difference within a single pair was 27% (Table 3).

Ground cover was remeasured in the Trumbull swales in September 2002 (before thinning), and the results showed a slight increase in the amount of litter and downed wood and the amount of live vegetation (Figure 10). The mean percent bare soil decreased from 22% to 14%.

Non-commercial thinning of the 5 treated swales in October 2002 increased the mean percent bare soil from 14% to 21% and decreased the percent live vegetation from 13% to 6% (Figure 10). The increase in percent bare soil was not significant ($p=0.39$), while the decrease in the percent live vegetation was significant at $p=0.10$. Thinning did not change the mean percent of litter and downed wood, and the variability decreased as all of the treated swales had at least 73% litter and downed wood (Appendix 5).

The change in cover due to the Hayman fire was much more drastic than the change in cover due to thinning (Figure 11). Seventeen of the 20 swales in upper Saloon Gulch burned at high severity, and 3 were classified as a mixture of moderate and high severity. On average, the percent of litter and downed wood decreased from 63% to less than 5%, and the percent of live vegetation decreased from 24% to less than 1% (Figure 11). Ash covered approximately 50% of the ground and the mean percent bare soil increased from 12% to 47%. Each of these changes was highly significant ($p<0.0001$). For individual swales, the maximum amount of litter and downed wood was only 11%, and the maximum amount of live vegetation was only 4% (Table 3). There was no change in the mean percent of rock cover. Since the ground cover was assessed on 3 July 2002 after the Hayman fire, these values do not reflect the increase in litter from falling needles in the swales that burned at a mixture of moderate and high severity. The mean percent of bare soil and ash in the swales burned at mixed severity decreased from 90% immediately after burning to 64% at the end of summer 2002 (D. Rough, Colorado State University, pers. comm., 2004).

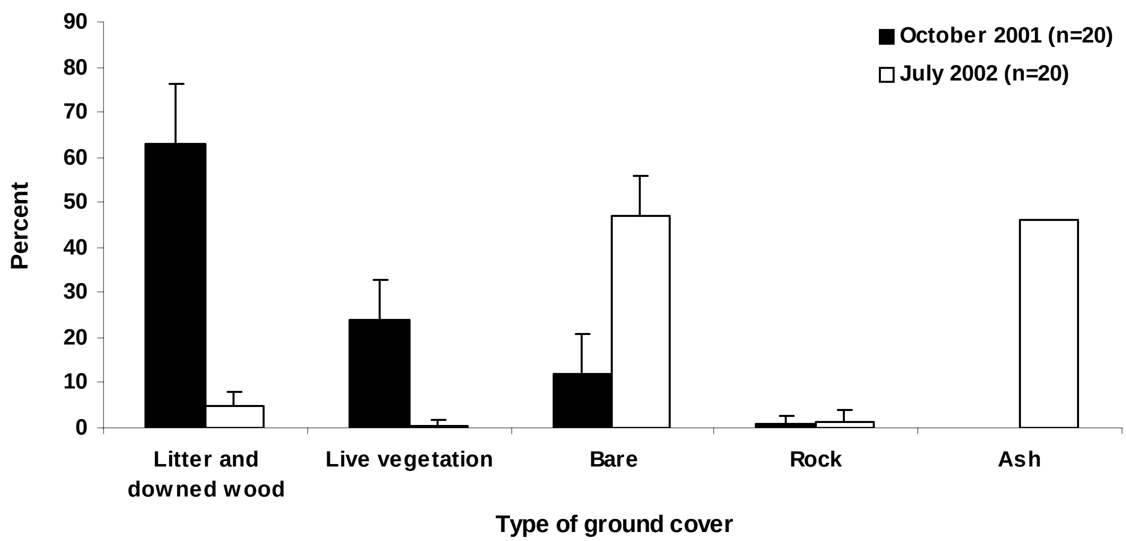


Figure 11. Mean percent cover for the swales in upper Saloon Gulch in October 2001 and after the Hayman wildfire in July 2002.

3.2.3. Soil particle-size distributions

The surface soils in the swales were generally very coarse. On average, the coarse and sand fractions accounted for roughly 90% of the sampled mass from the swales in both Trumbull and upper Saloon Gulch (Table 4). Percent silt averaged 6.1% in Trumbull and 9.0% in upper Saloon Gulch. Percent clay averaged less than 1% for both areas. Soil texture in Trumbull and upper Saloon Gulch was classified as gravelly coarse sandy loam.

On average, the surface soils in upper Saloon Gulch had slightly more coarse particles and substantially more silt and clay than the surface soils in Trumbull. Conversely, the surface soils in Trumbull averaged 45.5% sand as compared to 39.7% in upper Saloon Gulch (Table 4). The differences in the amount of silt and clay between Trumbull and upper Saloon Gulch were each significant at $p < 0.0001$.

Table 4. Mean particle-size distribution for the surface soils in Trumbull and upper Saloon Gulch. Numbers in parentheses are standard deviations from the means.

	Mean particle-size distribution (%)				
Site	Coarse	Sand	Silt	Clay	Organic matter
Trumbull	48.0 (6.1)	45.5 (5.1)	6.1 (1.8)	0.3 (0.2)	2.2 (0.9)
Upper Saloon Gulch	50.6 (7.7)	39.7 (6.1)	9.0 (3.1)	0.6 (0.2)	1.9 (0.5)

For individual swales, the proportion of coarse particles ranged from 30% to 68%, and the proportion of sand varied from 32% to 60% (Appendix 9). Percent silt varied from 3.2% to 15.0%, and percent organic matter ranged from 0.7% to 4.3%.

3.2.4. Soil water repellency

After the Hayman fire soil water repellency was measured in the unburned swales in Trumbull and the burned swales in upper Saloon Gulch and (Appendix 6). The soil water repellency in the unburned areas generally decreased with increasing depth, as the overall mean value was 55 dynes cm^{-1} at the soil surface, 59 dynes cm^{-1} at 3 cm and about 64 dynes cm^{-1} at 6 and 9 cm (Figure 12). For comparison, the mean soil water repellency in unburned areas adjacent to the Bobcat fire were 59 dynes cm^{-1} at 0 cm, 63 dynes cm^{-1} at 3 cm, and 69 dynes cm^{-1} at 6 cm (Hufmann and MacDonald, 2001). The soil water repellency under the tree canopy was slightly stronger than in the intercanopy areas at 0, 6 and 9 cm, but the reverse was true at 3 cm (Figure 12). The differences in soil water repellency between the canopy and intercanopy areas at 6 and 9 cm were significant at p=0.05 and p=0.07, respectively. The presence of fine roots was associated with stronger soil water repellency, and this may help explain the stronger soil water repellency under the tree canopy.

After the Hayman fire the soils in upper Saloon Gulch were much more water repellent than the unburned soils in Trumbull. At the soil surface the mean critical surface tension was 40 dynes cm^{-1}. Soil water repellency progressively weakened with increasing depth, as the mean values were 49 dynes cm^{-1} at 3 cm, 55 dynes cm^{-1} at 6 cm, and 63 dynes cm^{-1} at 9 cm. These values are very similar to the mean soil water repellency immediately after burning for high severity sites in the Bobcat fire (Hufmann and MacDonald, 2001). At upper Saloon Gulch the mean soil water repellency at 0 and 3 cm was significantly stronger under the canopy than in the intercanopy areas. The level of significance for these differences decreased from less than 0.0001 at 0 cm to 0.03 at 3 cm.

The decline in soil water repellency with increasing depth means that the greatest difference between the unburned and burned sites was at the soil surface (Figure 12).

The difference in soil water repellency between the burned and unburned swales was highly significant at 0 and 3 cm ($p<0.001$), but not at 6 or 9 cm ($p=0.07$).

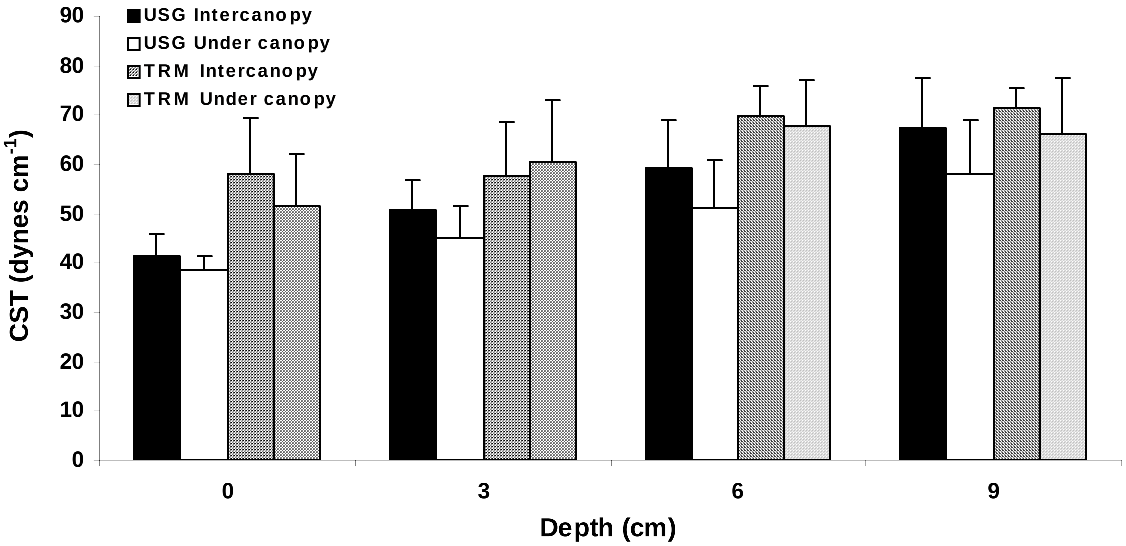


Figure 12. Mean critical surface tension in July 2002 in the intercanopy areas and under the tree canopy in upper Saloon Gulch and Trumbull. Lower values indicate stronger water repellency. Bars represent one standard deviation.

3.2.5. Sediment production

In 2001 only 3 of the 20 swales in Trumbull produced any sediment (Table 3). Each of the three swales that produced sediment was south facing, had from 34% to 43% bare soil located close to the sediment fence, and shallow soils. The mean sediment production from these swales was 0.67 kg m^{-2}, but the overall average sediment production for all the swales in Trumbull was only 0.12 kg m^{-2}. No sediment was produced from any of the 20 swales in upper Saloon Gulch or the two swales in Spring Creek (Table 5). The two bare hillslopes in Trumbull produced a total of 30 kg of sediment in 2001.

Table 5. Mean sediment production rates in 2001 and in 2002 from upper Saloon Gulch, Trumbull, and Spring Creek. NA indicates not applicable. * Spring Creek was not thinned in 2002.

	Mean sediment production (kg m^{-2})				
		2002			
	2001	Hayman Fire		Thinning	
Site		Before	After	Before	After
Upper Saloon Gulch	0	0	0.71	NA	NA
Trumbull	0.12	NA	NA	0	0
Spring Creek*	0	NA	NA	0	NA

In 2002, none of the swales in Trumbull or Spring Creek produced any sediment (Table 5). The upper Saloon Gulch swales did not produce any sediment prior to the Hayman fire. After the Hayman fire, all of the swales in upper Saloon Gulch produced large amounts of sediment. The total mass was 49,000 kg, but four of the fences were overtopped with sediment from the 11.2-mm storm on 21 July. This storm generated approximately 95% of the sediment produced in 2002, and the remaining 5% was generated by three subsequent, smaller storms. For Saloon Gulch, the mean sediment production rate in 2002 was 0.71 kg m^{-2}, and the range was from 0.3 to 1.2 kg m^{-2} (Table 5). On average, the control swales produced 0.72 kg m^{-2} as compared to 0.65 kg m^{-2} in the swales that were to have been treated (Appendix 8). A plot of sediment production versus contributing area shows that the variability in sediment production increased with increasing area, and a resulting need to log transform the sediment data (Figure 13).

Table 6. R^2 and p-values for sediment production versus selected swale characteristics for the swales in upper Saloon Gulch after the Hayman fire. NA indicates not applicable.

Dependent variable	Area (m^2)	Slope (%)	
		Axis	Side slopes
Log of sediment (kg)	0.80 (<0.001)	0.56 (<0.001)	0.22 (0.03)
Sediment per unit area (kg m^{-2})	NA	0.18 (0.06)	0.03 (0.45)
Log of sediment (kg mm^{-1})	0.80 (<0.001)	0.55 (<0.001)	0.22 (0.03)
Log of sediment (kg MJ ha^{-1} mm^{-1} h^{-1})	0.27 (0.01)	0.13 (0.1)	0.05 (0.3)

The log of the contributing area explained 80% of the variability in the log of sediment production (p<0.001) (Table 6; Figure 13). Axis slope explained 56% of the variability in sediment production (p<0.001), while the side slope only explained 22% of the variability (p<0.03) (Table 6). Normalizing sediment production by storm rainfall or erosvity did not significantly improve any of these relationships, probably because nearly all of the sediment was generated by the storm on 21 July.

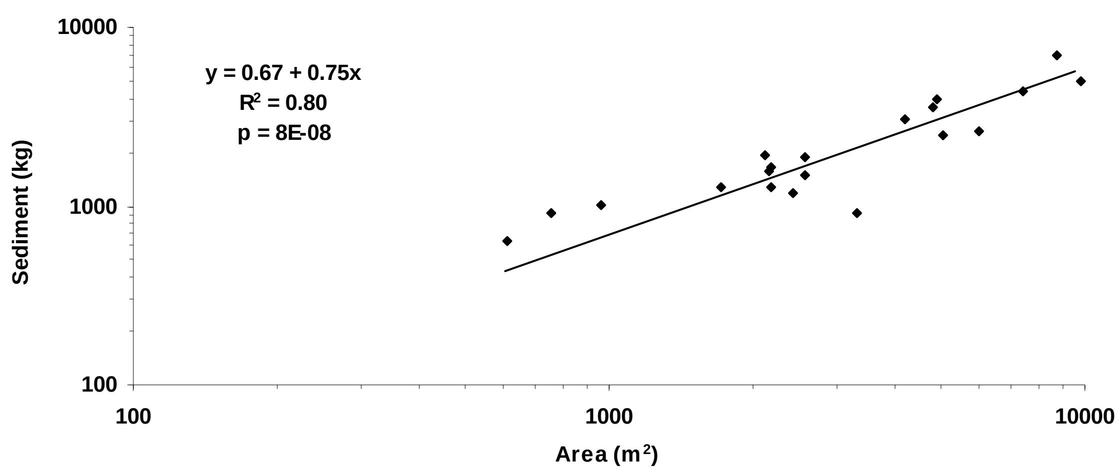


Figure 13. Sediment production in 2002 after the Hayman fire versus swale area.

Sediment production was significantly correlated with crest gauge height for the large storm on 21 July and a smaller storm on 21 September (Figure 14). Crest gauge height explained 55% of the variability in swale sediment production for the storm on 21 July 2002, and this was significant at $p<0.0001$. The relationship between sediment production and crest gauge height weakened as sediment production decreased. The storm on 21 September produced the second largest amount of sediment (1400 kg), and crest gauge height explained 33% of the variability in sediment production ($p<0.01$). The storms on 30 August and 11 October produced 950 kg and 67 kg respectively, and the relationship between crest gauge height and sediment production was not significant for either of these storms (Figure 14).

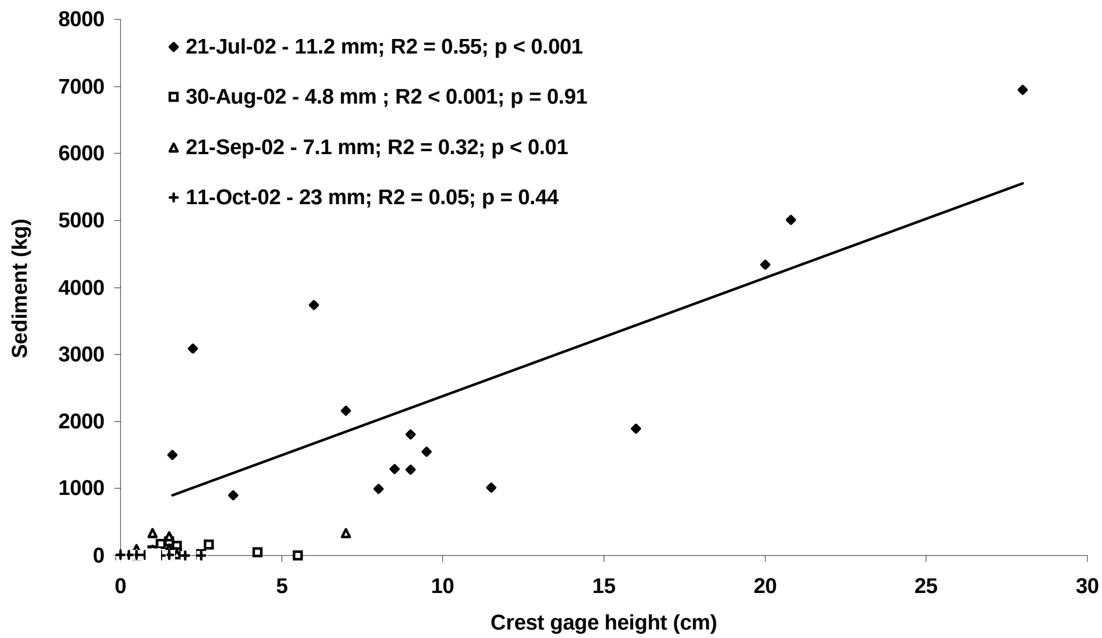


Figure 14. Sediment production versus maximum crest gage height for 4 storms in summer 2002 in upper Saloon Gulch. Each point represents a different swale (n=16). The regression line is for the storm on 21 July.

3.2.6. Particle-size distribution of the eroded sediment

The eroded sediment was dominated by coarse particles and sand (Figure 15). For both Trumbull and upper Saloon Gulch the proportion of coarse material in the eroded sediment was less than in the soils. This difference was greater for the swales in Trumbull, but the level of significance was only 0.06 because of the small sample size (n=3). The eroded sediment in Trumbull had more sand and significantly more silt than the surface soils (Figure 15a). The eroded sediment in upper Saloon Gulch had slightly more sand than the surface soil and significantly more silt ($p<0.01$) (Figure 15b). The eroded sediment in Trumbull and upper Saloon Gulch had 3% and 9% organic matter, respectively. The amount of organic matter in the eroded sediment was significantly higher than in the soils ($p=0.01$ and $p<0.001$, respectively). In Trumbull the larger amount of organic matter was attributed to the relatively large amount of litter captured in the fences. In upper Saloon Gulch the larger amount of organic matter is due to the large amount of ash and charred material that was washed into the sediment fences by the overland flow.

The size distribution of the eroded sediment varied with storm size (Figure 16). The biggest storm on 21 July 2002 yielded a significantly higher proportion of coarse sediment than the smaller storms on 21 September and 11 October ($p=0.01$). The proportion of sand in the eroded sediment tended to increase with decreasing storm size, but this increase was not significant ($p=0.26$). The storm on 11 October 2002 yielded a significantly higher proportion of silt compared to the other three storms ($p<0.01$). This was the largest storm with 23 mm of rain, but this fell over four-and-a-half hours and the maximum 30-minute intensity was only 4.1 mm hr^{-1}.

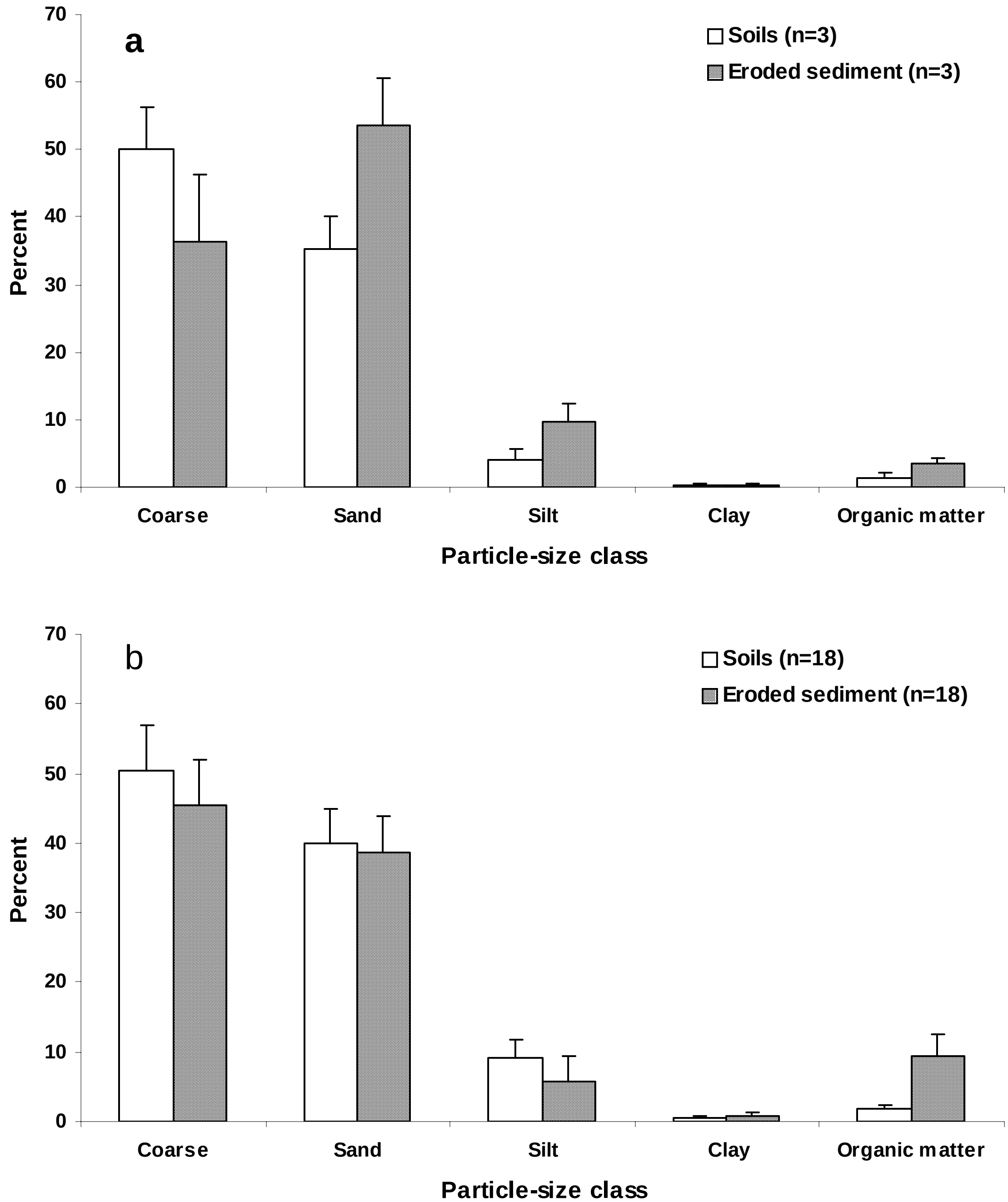


Figure 15. Composition of the eroded sediment versus the surface soils for: (a) Trumbull, and (b) upper Saloon Gulch. Bars represent one standard deviation.

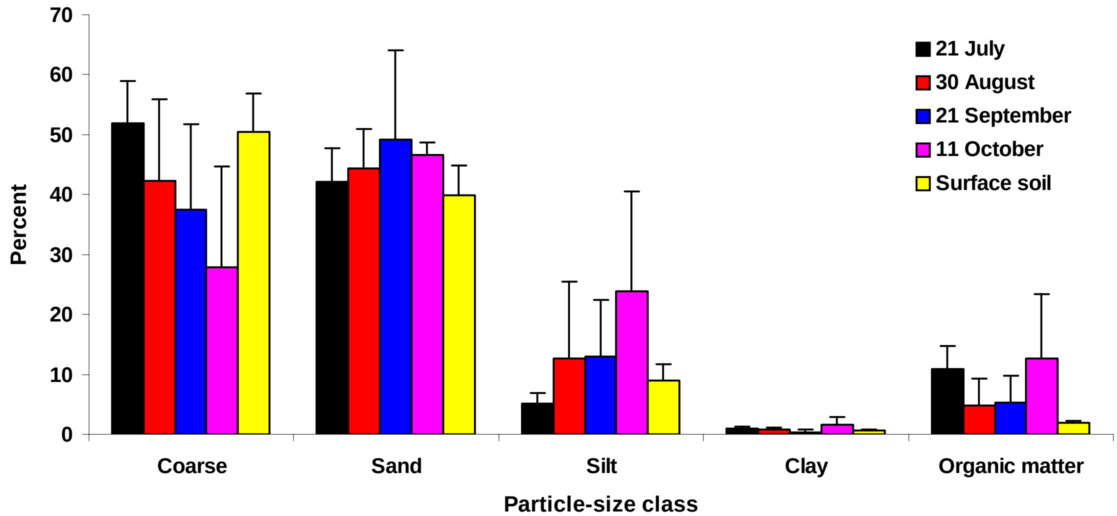


Figure 16. Storm-by-storm composition of the sediment eroded in upper Saloon Gulch in 2002 versus the surface soils.

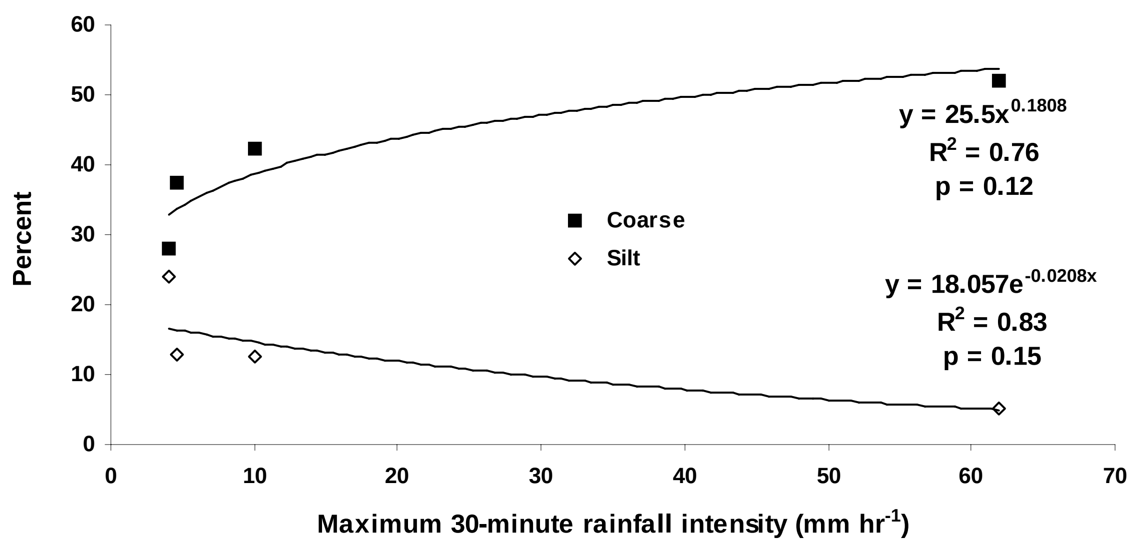


Figure 17. Percent coarse and percent sand in the eroded sediment versus maximum 30-minute rainfall intensity for the 4 storms in upper Saloon Gulch in 2002.

Storm intensity explained 76% of the variability in the proportion of coarse particles in the eroded sediment, and 83% of the variability in the proportion of silt.

However, these relationships were significant only at p=0.12 and p=0.15, respectively (Figure 17). Since the proportion of sand also tended to increase with increasing storm intensity, it appears that the smaller storms are selectively detaching and transporting the smaller particles, and the larger storms are able to detach and transport a more representative mixture of the surface soils.

3.3. Roads

3.3.1. Road characteristics and traffic

The road survey covered 13.5 km of unpaved forest roads and identified 204 individual segments (Table 7). The Spring Creek road was 6.67 km long or nearly 50% of the total distance. There were 5.67 km of roads in upper Saloon Gulch and only 1.13 km in Trumbull.

The average segment length was 76 m, but this varied from 56 m in Spring Creek to 95 m in Trumbull (Table 7). On average, the active road width was 2.5 m, but the roads in upper Saloon Gulch tended to be slightly narrower. The mean road slope was 12% in Trumbull as compared to 7% in upper Saloon Gulch and 6% in Spring Creek (Table 7), and this difference is attributed to the steeper terrain in the Trumbull area.

Eighty percent of the roads in Trumbull were in a midslope position and 20% were in the valley bottom, while at least 90% of the roads in upper Saloon Gulch and Spring Creek were on ridgetops (Table 7). Seventy percent of the roads in Trumbull had less than 5% cover while nearly 90% of the roads in upper Saloon Gulch and in Spring Creek were classified as having more than 5% cover. With respect to drainage, nearly half of the roads were outsloped and another one-third were classified as planar.

Insloped roads were rare except for one long segment in Trumbull. On average, 63% of the roads did not have a distinct drainage location, while 26% drained to culverts. Ninety-three percent of the roads had no inside ditch.

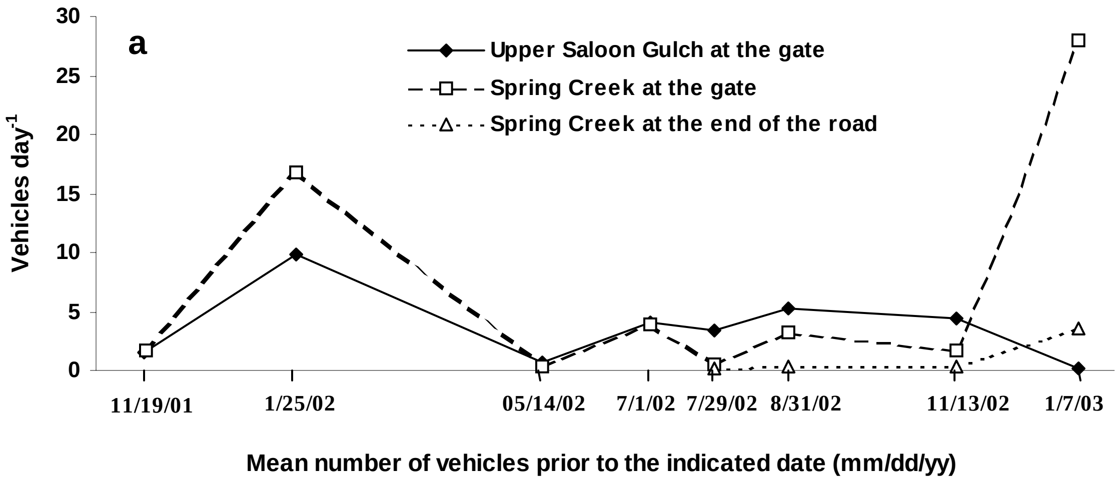
Rilling at drainage outlets was relatively uncommon except at Trumbull. Sediment plumes were observed for 71% of the road length in Trumbull, 34% of the road length in upper Saloon Gulch, and 42% of the road length in Spring Creek. At least three-quarters of the roads in upper Saloon Gulch and Spring Creek fell into connectivity classes 1 and 2 as compared to just one-third of the roads in Trumbull. Two-thirds of the roads in Trumbull were connected to the stream network (connectivity class 4) as compared to 19% of the roads in upper Saloon Gulch and 9% of the roads in Spring Creek.

From 19 October 2001 to 7 January 2003 the mean traffic loads in upper Saloon Gulch and Spring Creek were 7.0 and 3.7 vehicles per day (Figure 18). The number of vehicles per day increased markedly in December 2001 in upper Saloon Gulch and Spring Creek due to Christmas tree sales (Figure 18a). There was an even larger increase in the number of vehicles in Spring Creek in late 2002 because the fire precluded any Christmas tree traffic in upper Saloon Gulch. On average, only 7% of the vehicles recorded at the Spring Creek gate reached the traffic counter at the end of the road.

Table 7. Summary of the surveyed road characteristics by site. Values are weighted averages by road length or number of segments. Numbers in parentheses represent the percent of total road distance for each area.

	Site		
	Trumbull	Upper Saloon Gulch	Spring Creek
Total distance surveyed (m)	1134	5672	6672
Number of road segments	12	72	120
Average segment length (m)	95	79	56
Average slope (%)	12	7	6
Average active width (m)	2.6	2.2	2.6
Average total width (m)	3.8	6.0	7.1
Hillslope gradient below road (%)	26	19	15
Hillslope gradient above road (%)	24	16	14
Traffic (21 September 2001 - 7 January 2003)	1643	3136	6295
Hillslope position (number of segments)			
Ridgetop (<100 m from the ridgetop)	0	67 (96)	111 (90)
Midslope	9 (80)	5 (4)	3 (3)
Valley bottom (within 100 m of a stream)	3 (20)	0 (0)	6 (7)
Surface cover on active road surface (number of segments)			
Bare (0-5%)	9 (72)	6 (7)	13 (12)
Partly vegetated (5-15%)	3 (28)	47 (50)	97 (76)
Well vegetated (>15%)	0	19 (43)	10 (12)
Road surface shape (number of segments)			
Insloped	1 (36)	6 (7)	11 (10)
Outsloped	5 (30)	34 (50)	58 (43)
Outsloped with berm	0	0	3 (2)
Planar	0	25 (30)	32 (31)
Planar with berms on both sides	6 (33)	0 (0)	2 (1)
Crowned	0	6 (13)	14 (13)
Inside ditch (number of segments)			
Yes	0	7 (8)	11 (13)
No	12 (100)	65 (92)	109 (87)
Drainage outlet (number of segments)			
Culvert	2 (14)	20 (38)	26 (27)
Waterbar/dip	0	0	18 (17)
Pushout	0	1(2)	18 (14)
No drainage	10 (86)	51 (60)	58 (42)
Rilling below outlet (number of segments)	5 (67)	8 (9)	17 (17)
Sediment plumes (number of segments)	8 (71)	20 (34)	45 (42)
Connectivity class - number of segments			
1=No signs of concentrated flow	4 (29)	52 (66)	75 (60)
2=Flow for less than 20 m	2 (4)	6 (11)	29 (25)
3=Flow greater than 20 m but more than 10 m to the stream	0	3 (4)	7(6)
4=Continuous channel or plume to the stream	6 (67)	11 (19)	9 (9)

At Trumbull the mean traffic load over the study period was 1.8 vehicles per day, or 26% of the value at Spring Creek. The increased traffic in fall 2001 (Figure 18b) was probably due to the preparation and execution of thinning activities by the U.S. Forest Service and Denver Water. In May 2002 the Trumbull road was regraded and extended to accommodate the increase in traffic due to the Schoonover wildfire. On average, 50% of the vehicles recorded at the gate passed the traffic counter installed halfway between the gate and the Schoonover fire.



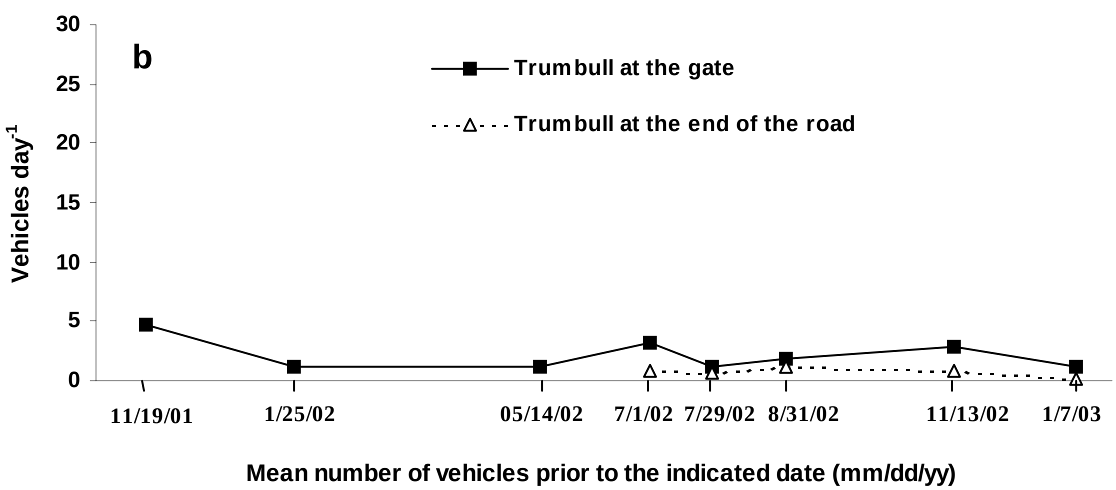


Figure 18. Mean number of vehicles prior to the indicated date at: (a) upper Saloon Gulch and Spring Creek; and (b) Trumbull.

3.3.2. Road segment characteristics and sediment production

Table 8. Road segment characteristics and sediment production for the segments with sediment fences in upper Saloon Gulch, Trumbull, and Spring Creek in 2001 and in 2002. NA indicates that a fence was not installed in 2001. * indicates that the road drainage was diverted away from the fence after the road was regraded in May 2002.

Site	Sediment fence no.	Road Segment Characteristics: Length (m)	Slope (%)	Active width (m)	Total width (m)	Ground cover (%): Bare 2001	Bare 2002	Litter and downed wood 2001	Litter and downed wood 2002	Vegetation 2001	Vegetation 2002	Sediment production (kg m^{-2}) 2001	2002
TRM	R 9	37.2	16	2.4	4.0	54	78	46	22	0	0	0.0	1
TRM	R 8	47.8	15	2.1	3.2	49	61	48	39	2	0	4.5	0
TRM	R 7	210.8	18	2.5	4.0	36	89	61	10	2	0	2.8	*
TRM	R 24	52.3	18	2.4	4.3	NA	90	NA	10	NA	0	NA	*
TRM	R 25	59.3	12	2.1	3.0	NA	50	NA	49	NA	1	NA	*
TRM	R 26	45.1	15	2.1	2.9	NA	50	NA	49	NA	1	NA	*
TRM	R 27	30.0	14	2.2	2.7	NA	24	NA	75	NA	1	NA	*
Mean		68.9	15.4	2.3	3.4	46	63	51.7	36.3	1.3	0.4	2.4	0.4
USG	R 11	57.2	10	3.9	7.2	100	100	0	0	0	0	2.9	2.7
USG	R 7	219	8	2.2	4.3	83	98	9	9	8	1	0.1	1
Mean		138.1	9.0	3.1	5.8	92	99	4.5	4.5	4.0	0.5	1.5	1.6
SC	R 15	74.0	8	3.0	5.6	NA	96	NA	4	NA	0	NA	0.0
SC	R 14	74.0	10	2.4	7.4	NA	95	NA	5	NA	0	NA	0.6
SC	R 13	22.0	4	2.85	6.9	NA	94	NA	0	NA	6	NA	0.2
SC	R 11	22.1	6	3.1	7.3	95	98	2	2	3	0	0	0.2
SC	R 10	25.1	6	3.0	4.9	84	100	13	0	3	0	0	1.4
SC	R 9	118.9	6	2.5	6.0	86	98	13	2	1	0	1.9	0.8
SC	R 8	104.9	10	3.7	7.2	80	99	13	1	4	0	3.1	0.3
SC	R 7	58.8	9	2.6	6.2	91	98	8	1	1	1	3.8	0.5
SC	R 6	49.7	6	2.2	5.4	82	100	17	0	1	0	0.9	0.1
SC	R 5	54.0	9	2.7	7.2	90	97	9	3	1	0	1.2	0.2
SC	R 4	85.0	8	2.3	7.0	83	99	9	1	6	0	4.0	0.3
SC	R 2	46.6	10	3.0	6.4	84	84	13	16	1	0	5.4	0.1
Mean		61	8	2.8	6.5	86	97	10.8	2.9	2.3	0.6	2.3	0.4

The average length and slope of the road segments with sediment fences generally were similar to the larger survey except for one very long segment at upper Saloon Gulch (Table 8). Individual segments varied in length from 22 m to 219 m. When stratified by area, the road segments with sediment fences averaged 1-3% steeper than the mean slopes from the road survey. The slopes of the road segments with sediment fences varied from 6% to 16%. In Trumbull and Spring Creek the active road widths of the segments with sediment fences were nearly identical to the mean value from the road survey. At upper Saloon Gulch the active width of the two road segments with sediment fences was 3.1 m as compared to the mean of 2.2 m from the road survey (Table 8).

From July 2001 to July 2002 the percent bare soil for the 21 road segments with sediment fences increased from 78% to 93% (Figure 19). This increase was primarly due to the 12% decrease in the amount of litter and downed wood (Table 8). The greatest change was in Trumbull, as the regrading and traffic associated with the Schoonover fire decreased the amount of litter and downed wood from 52% to 24% and increased the percent bare soil from 46% to 76% (Figure 19). The relatively dry weather in summer 2002 and the increase of traffic due to the Hayman fire were probably responsible for the loss of ground cover on the roads in upper Saloon Gulch and Spring Creek.

In contrast to the unburned swales, all of the road segments with sediment fences produced some sediment in both 2001 and in 2002 (Table 8). In 2001 the mean sediment production rate from all road segments was 2.1 kg m^{-2}. There was considerable variability among segments, as the range was from 0.01 kg m^{-2} to 5.4 kg

m^{-2} (Table 8). The mean sediment production rates for each area were surprisingly similar despite the differences in traffic, ground cover, and rainfall.

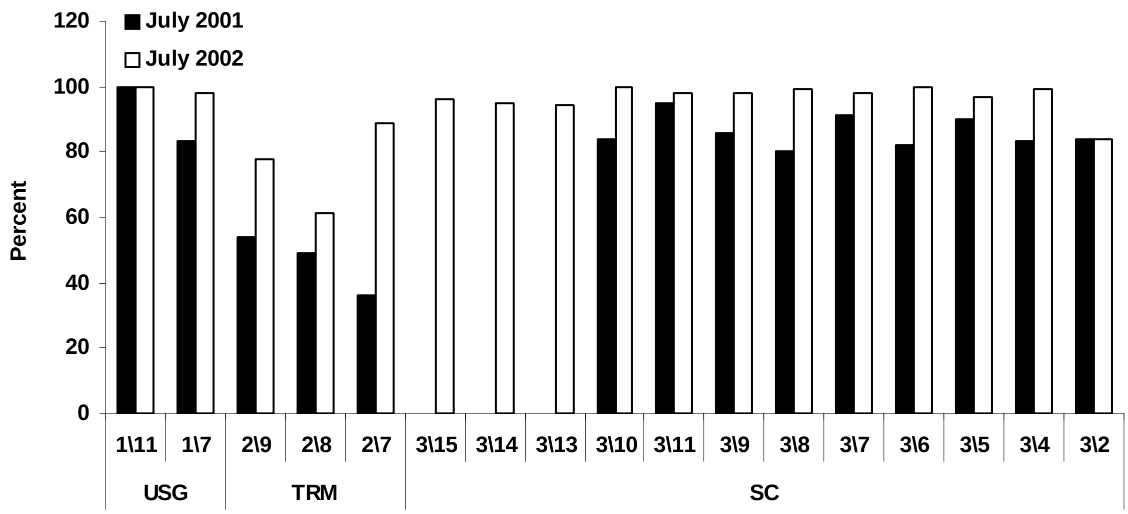


Figure 19. Percent bare soil for the road segments with sediment fences in upper Saloon Gulch, Trumbull, and Spring Creek in July 2001 and July 2002. Segments are in order from the gate or main road. No data are available for segments 3/15, 3/14, and 3/13 in July 2001.

In 2002 the mean road sediment production rate declined to 0.5 kg m^{-2}, or only 24% of the value from 2001. Mean sediment production rates in Spring Creek and Trumbull were 0.4 kg m^{-2} as compared to 1.6 kg m^{-2} in upper Saloon Gulch. The highest value was 2.7 kg m^{-2} for segment R 11 in upper Saloon Gulch (Table 8).

Univariate analysis showed that active road surface area was the variable most strongly correlated with annual road sediment production (R^2 =0.34; p = 0.01) (Table 9). The correlation of sediment production to total contributing area was slightly weaker (R^2 = 0.30; p = 0.02). Since field observations indicated that the cutslopes and road shoulders were not actively eroding, the sediment production rates from the road segments were normalized by active road area rather than total road area. Percent slope was not significantly related to annual sediment production. Total road area times slope had a slightly higher R^2 of 0.37 ($p = 0.01$).

Table 9. R^2 and p-values (in parentheses) for road segment sediment production versus segment characteristics. Significant relationships are in bold.

Segment characteristics	Storm events					**Total sediment production**
	31-Aug-01	14-May-02	21-Jul-02	31-Aug-02	11-Oct-02	
Active area (m^2)	**0.55 (0.06)**	0.19 (0.16)	**0.55 (0.09)**	0.14 (0.42)	0.01 (0.78)	**0.34 (0.01)**
Total area (m^2)	**0.44 (0.10)**	0.14 (0.23)	**0.55 (0.09)**	0.10 (0.50)	0.02 (0.73)	**0.30 (0.02)**
Slope (%)	0.31 (0.20)	0.01 (0.75)	0.06 (0.64)	0.35 (0.16)	0.18 (0.25)	0.12 (0.16)
Active area*slope	**0.71 (0.02)**	0.09 (0.34)	0.40 (0.18)	0.17 (0.36)	0.00 (0.88)	**0.34 (0.01)**
Total area*slope	**0.71 (0.02)**	0.08 (0.38)	0.43 (0.16)	0.14 (0.40)	0.00 (0.97)	**0.37 (0.01)**
Sample size	7	12	6	7	9	17
Mean erosion rate (kg m^{-2})	2.9	0.3	0.1	0.3	0.2	0.6

On a storm-by-storm basis, the strength of the relationships between road surface characteristics and sediment production were more variable (Table 9). The highest erosion rate occurred as a result of a 27-mm storm on 13 August 2001. For this storm active or total road surface area times slope each explained 71% of the variability in sediment production. For the other four smaller storms, none of the road segment characteristics was significantly correlated with road sediment production (p values $\geq$ 0.06). Storms as small as 4.8 mm or 5 MJ mm ha^{-1} hr^{-1} caused erosion rates of 0.04 kg m^{-2}.

Annual road sediment production was significantly related to total summer rainfall and total summer erosivity, but these variables explained only 24% and 28% of the variability, respectively (Figure 20). For one road segment the nearest rain gauge was 2.5 km away, and the spatial variability in rainfall explains how this segment could produce nearly 500 kg of sediment from two millimeters of rainfall and no erosivity

(Figure 20). This point was excluded from the regression calculations because the rainfall data were obviously erroneous. The spatial variability of the rainstorms and the limited number of sediment-producing storms may explain the weak relationships between sediment production, total precipitation, and total erosivity (Figure 20).

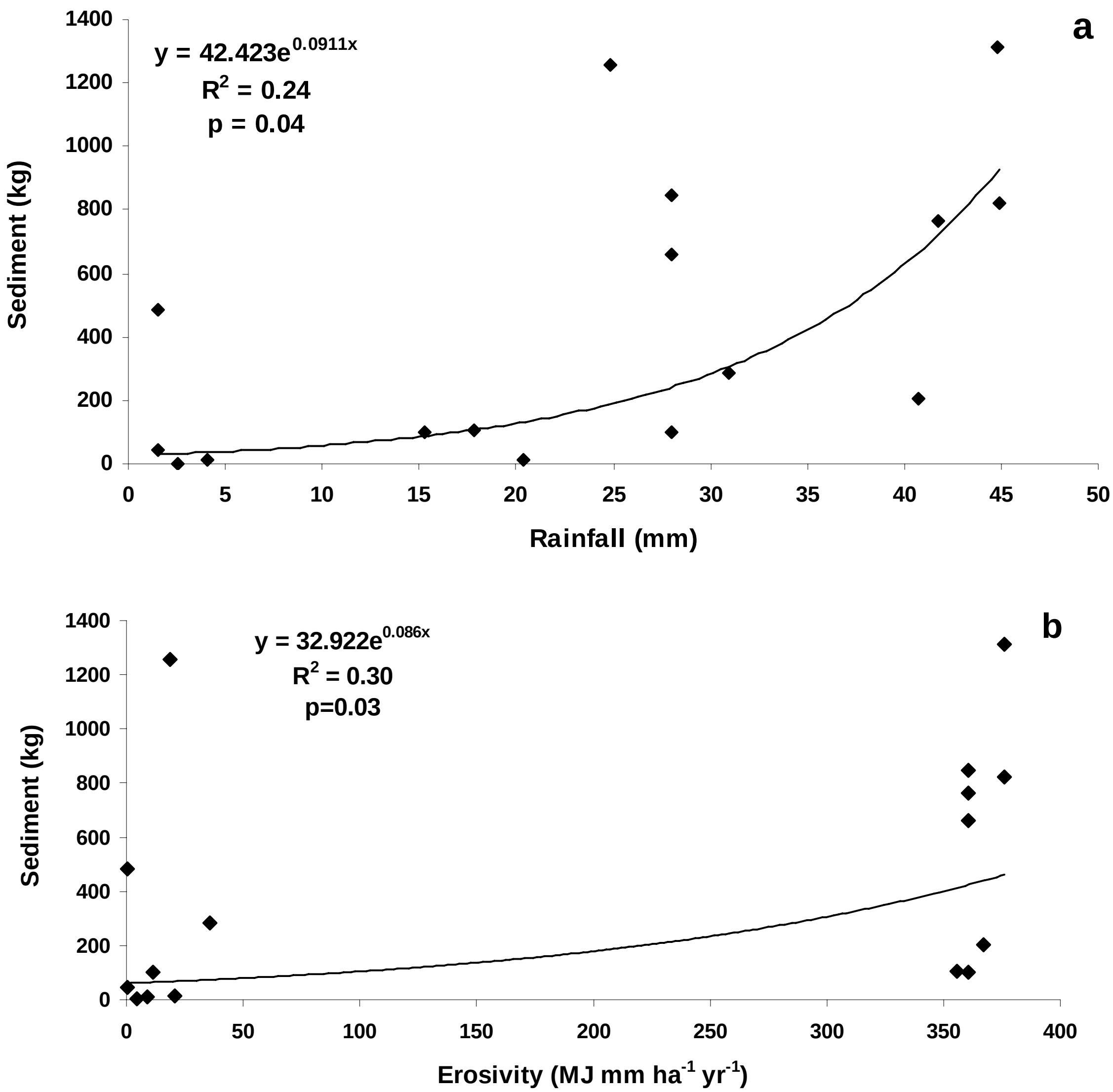


Figure 20. Annual road sediment production versus: (a) summer rainfall, and (b) summer erosivity.

Multiple regression analysis showed that the best model used only area times slope. Adding percent bare soil or any of the rainfall terms did not significantly improve the relationship with sediment production (Table 10). However, if the sediment production data were normalized by storm depth or storm erosivity, percent bare soil was significantly correlated with road segment sediment production (Table 10). As data are collected from more sediment-producing storms or more years with better rainfall data, storm rainfall or storm erosivity may become a more significant predictor.

Table 10. R^2 and p-values for normalized sediment production rates from the road segments versus segment characteristics. P-values are in parentheses. Significant relationships are in bold.

Sediment production	Percent bare soil	Slope	Active area* slope	Active area* slope + percent bare soil
kg	0.005 (0.8)	0.13 (0.2)	**0.34 (0.01)**	**0.36 (0.05)**
kg mm^{-1}	**0.57 (<0.001)**	**0.33 (0.02)**	0.005 (0.8)	**0.59 (0.003)**
kg MJ mm ha^{-1} yr^{-1}	**0.73 (<0.0001)**	**0.34 (0.02)**	<0.001 (0.9)	**0.73 (<0.001)**

3.3.3. Particle-size distribution

Like the soils in the swales, the surface of the roads was dominated by coarse particles and sand. On average, the coarse and sand fractions accounted for approximately 91% of the soil mass (Table 11). The mean proportion of silt varied from 4-9%, and the mean proportions of clay and organic matter were each less than 1%. There was considerable variability between segments, as the coarse fraction ranged from 28% to 53% and percent sand ranged from 41% to 63% (Appendix 13). For individual segments the proportion of silt varied from 2% to 15%, while the proportions of clay and organic matter varied from less than 1% to 3%. The road surface in Trumbull had substantially more coarse particles and less silt than the roads in upper Saloon Gulch and Spring Creek (Table 11).

Table 11. Mean particle-size distribution for the road surfaces in Trumbull, upper Saloon Gulch, and Spring Creek.

	Mean particle-size distribution (%)				
Site	Coarse	Sand	Silt	Clay	Organic matter
Trumbull	48.5 (2.7)	46.8 (2.9)	4.2 (0.6)	0.5 (0.1)	0.7 (0.1)
Upper Saloon Gulch	40.3 (6.8)	50.2 (7.4)	9.0 (2.3)	0.5 (0.1)	0.6 (0.2)
Spring Creek	38.7 (7.0)	52.9 (6.4)	7.8 (1.6)	0.6 (0.3)	0.8 (0.8)

On average, the road surfaces had a significantly smaller proportion of coarse particles and more sand than the surface soils in the swales ($p<0.0001$). The exception was at Trumbull, where the road surface and the surface soils in the swales had similar amounts of coarse particles and sand.

Relative to the road surface, the eroded sediment had proportionally smaller amounts of coarse particles and a higher proportion of silt, clay, and organic matter (Figure 21). On average, the eroded sediment contained 18% silt as compared to 7% for the road surface, and this difference was significant at $p=0.005$. The higher proportions of clay and organic matter in the eroded sediment were also significant at $p\leq0.01$. These data indicate preferential erosion and transport of the smaller and lighter fractions (Figure 21).

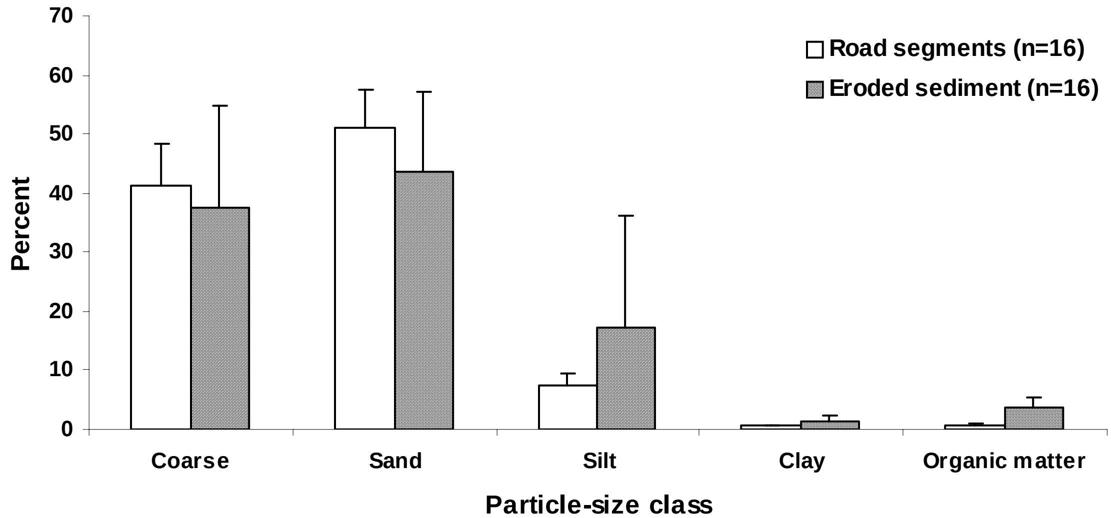


Figure 21. Mean particle-size distribution of the eroded sediment versus the road surface in upper Saloon Gulch, Trumbull, and Spring Creek. The proportion of each size fraction in the eroded sediment is weighted by the amount of sediment produced from each storm.

The particle-size distribution of the eroded sediment had a noisy but significant relationship with storm erosivity (Figure 22). The proportion of coarse particles tended to increase with increasing storm erosivity while the proportion of silt tended to decrease. The data from the road fence that was 2.5 km away from a rain gauge was excluded in the regression analysis, as the measured sediment could not have been generated by the measured rainfall. The proportions of sand, clay, and organic matter in the eroded sediment showed no clear pattern with storm erosivity.

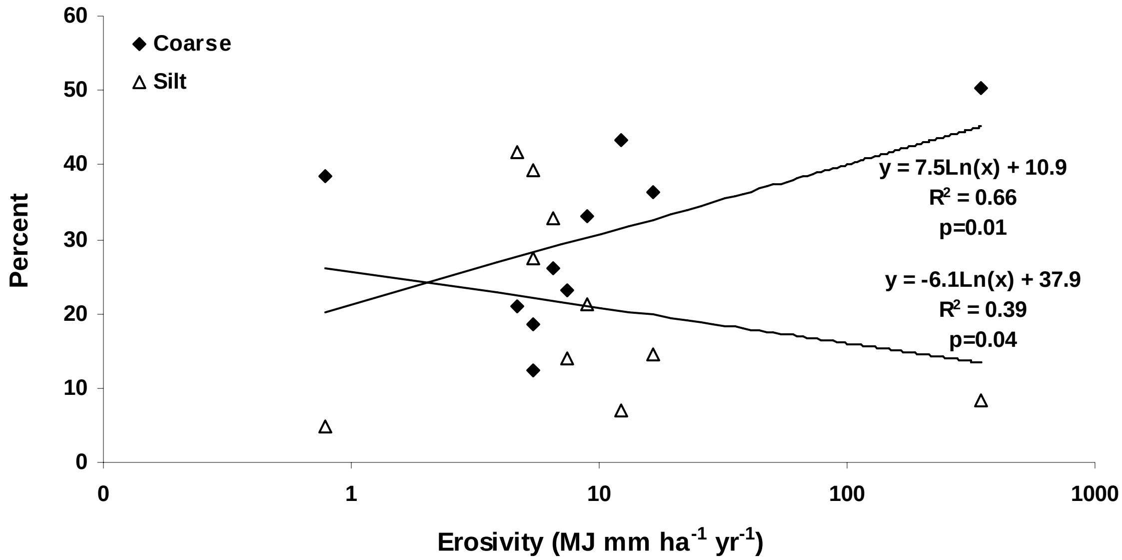


Figure 22. Percent coarse and silt fractions in the eroded sediment versus storm erosivity. The regression lines do not include the two data points on the far left side.

3.3.4. Road connectivity

Of the 204 surveyed road segments, 64% showed no evidence of concentrated flow draining from the road. Another 18% of the road segments had rills or sediment plumes that extended for less than 20 m. Twenty-six segments (15%) were connected to the stream network, and these represent only 6% of the total road length. Approximately two-thirds of the road segments in Trumbull were connected to the stream network as compared to 19% of the road segments in upper Saloon Gulch and 9% of the road segments in Spring Creek (Table 7). This difference can be partly explained by slope position, as 80% of the roads at Trumbull were in a midslope position, while more than 90% of the roads in upper Saloon Gulch and Spring Creek were on ridgetops. In addition, the mean road segment length was longer in Trumbull than in upper Saloon Gulch and Spring Creek, so the road segments in Trumbull would generate more overland flow. Finally, the adjacent side slopes in Trumbull were steeper than in the other two areas, and the combination of increased runoff and steeper slopes would tend to increase road connectivity (Wemple et al., 1996).

The length of rills and sediment plumes were measured below 69 road drainage outlets. Approximately 70% of the rills and sediment plumes were below road segments that did not have a well-defined drainage point, 20% were below a pushout, and only 5% were from road segments with culverts.

The mean rill length was 27 m and the mean sediment plume length was 23 m (Appendix 10). Road surface area was a much better predictor of rill length, rill volume, and sediment plume length than segment slope (Table 12). The best single predictor was active road area times slope, and this explained 43% of the variability in rill length, 31% of the variability in rill volume, and 54% of the variability in sediment plume length (Table 12). All of these relationships were significant at $p \leq 0.01$. Neither roughness class nor downslope gradient were significantly related to rill length, rill volume, or sediment plume length.

Table 12. R^2 and p-values (in parenthesis) for the relationships between selected road segment and rill length, rill volume, and sediment plume length. The best predictors are shown in bold.

	Rill length (m)	Rill volume (m^3)	Sediment plume length (m)
Segment characteristics	R^2 (p-value)	R^2 (p-value)	R^2 (p-value)
Road surface area (m^2)	0.38 (0.0003)	0.12 (0.06)	0.23 (<0.0001)
Road length (m)	0.32 (0.001)	0.083 (0.12)	0.20 (0.0001)
Segment slope (%)	0.02 (0.42)	0.07 (0.15)	0.077 (0.02)
Active area*slope	**0.43 (0.01)**	**0.31 (0.001)**	**0.54 (<0.0001)**
Downslope gradient (%)	0.03 (0.34)	0.01 (0.51)	0.01 (0.42)

Rill cross-sectional area was positively related to connectivity class (p = 0.0009), and the mean cross-sectional area of rills below segments in connectivity class 4 were approximately 50% greater than the mean area of rills below segments in connectivity classes 2 and 3 (Figure 23). Rill cross-sectional area decreased with increasing distance from the road, indicating a continuing infiltration of the road surface runoff (Figure 23).

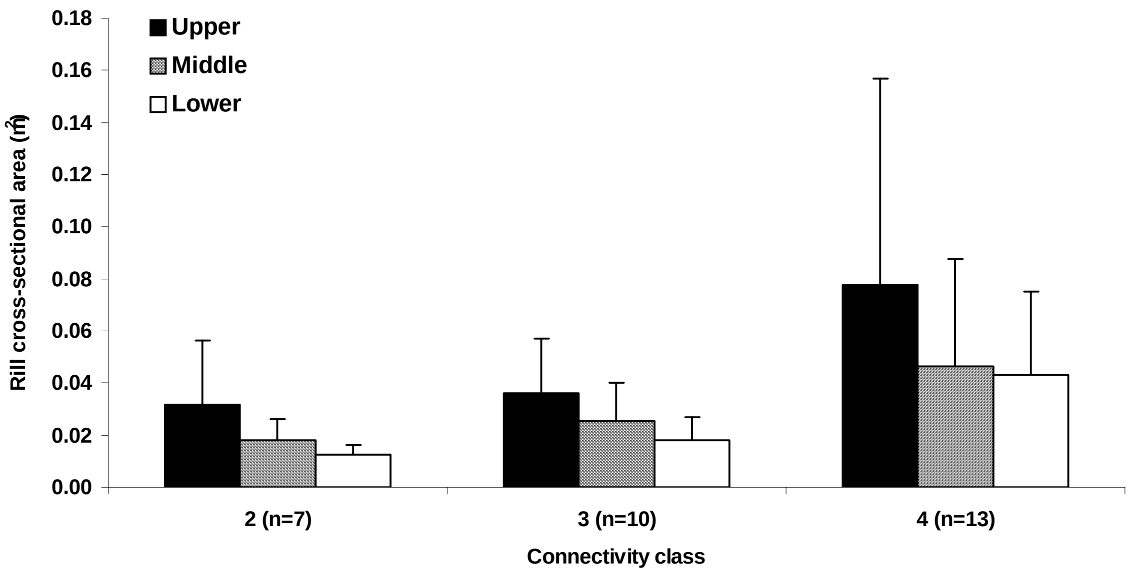


Figure 23. Cross-sectional area of the upper, middle, and lower portion of the rills below road segments versus connectivity class. Bars represent one standard deviation.

3.4. Small-catchment scale

3.4.1. Channel morphology

The drainage area above the sample reach in Brush Creek was 6.2 km^2, or nearly twice the area above the sample reaches on Saloon Gulch and No Name Creek in Trumbull (Table 13). The channel gradient in Brush Creek was 8.4% as compared to 3.5% in Saloon Gulch and 2.3% in No Name Creek. The estimated bankfull channels

Table 13. Channel characteristics for Saloon Gulch, Trumbull, and Brush Creek in 2001.

	Site		
Channel Characteristics	**Saloon Gulch**	**No Name Creek**	**Brush Creek**
Drainage area (km^2)	3.4	3.3	6.2
Mean gradient (%)	3.5	2.3	8.4
Date of survey (dd/mm/yr)	01/11/01	15/08/01	06/08/01
Bankfull channel width (m)	0.76	0.36	0.67
Bankfull depth (m)	0.08	0.05	0.12
Discharge on survey date (L s^{-1})	0.3	~0	1.1
Percent eroding banks	4	30	13
D_{84} (mm)	13	15	33
D_{50} (mm)	7	6	12
Percent fines <8 mm	62	61	35

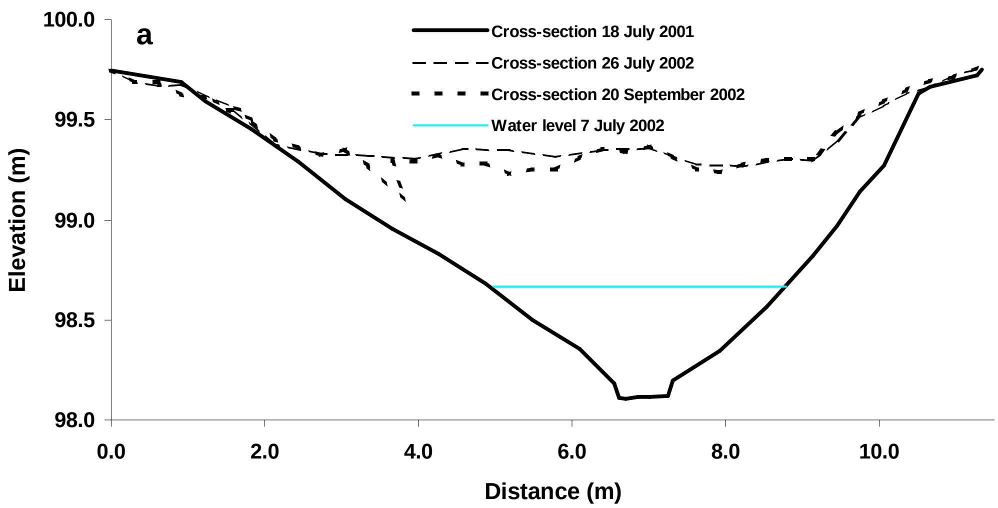
were all less than a meter wide and only a few centimeters deep. As might be expected, the estimated bankfull channel in the larger and steeper Brush Creek catchment was slightly larger than the bankfull channel in Saloon Gulch, while the bankfull channel in No Name Creek was much smaller (Table 13). At the time of the surveys in 2001 the discharge ranged from approximately zero to 1.1 L s^{-1} (Table 13).

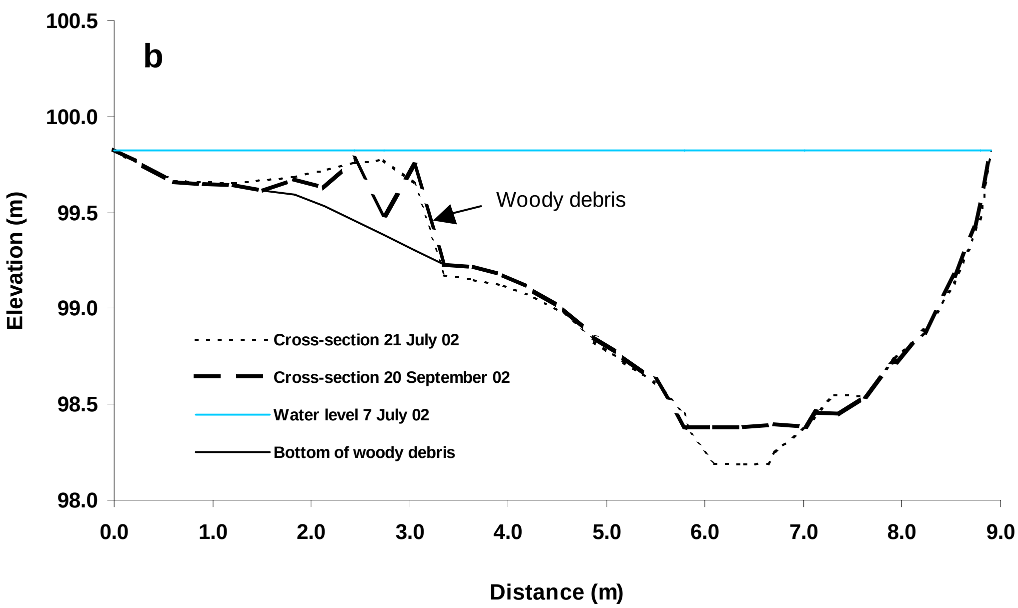
The banks in Saloon Gulch and Brush Creek were relatively stable, while 33% of the banks in No Name Creek were classified as being actively eroded (Table 13). The bed material in the larger and steeper Brush Creek catchment was much coarser than the bed material in Saloon Gulch and No Name Creek (Table 13).

In June 2002 the Hayman fire burned approximately 80% of the Saloon Gulch and Brush Creek catchments. Approximately 40-50% of each catchment was burned at high severity (USDA Forest Service, 2003). The resulting increases in runoff and erosion caused major changes in the study reaches in Saloon Gulch and Brush Creek. Observations of ash and sediment deposits after the 15-mm storm on 7 July 2002 indicated that the peak flows were approximately 0.5 m deep in Saloon Gulch and 1.6 m deep in Brush Creek (Figure 24). Both flumes filled with sediment, ash, and organic debris. Both flumes were cleaned out, but the second storm on 21 July 2002 completely buried the flume in Saloon Gulch with up to 1.3 m of sediment (Figure 24a). In Brush Creek the same storm deposited about 0.5 m of sediment (Figure 24b), and completely filled the flume with sediment, ash, and organic debris. The stage recorder was destroyed, and a rock nearly 1 m in diameter was lodged in the mouth of the flume.

The deposited sediment increased the proportion of particles smaller than 8 mm from 35% to 70% in Brush Creek, and from 62% to 77% in Saloon Gulch (Figure 25). The proportion of banks classified as actively eroding jumped from 13% to 67% in Brush Creek, and from 4% to 32% in Saloon Gulch (Figure 26).

The cross-section in No Name Creek in Trumbull show minimal change from the first survey in summer 2001 to October 2003, which was one year after thinning (Figure 24c). There were no detectable changes in either the amount of eroding banks or the size of the bed material (Appendix 16).


a
Cross-section 18 July 2001
Cross-section 26 July 2002
Cross-section 20 September 2002
Water level 7 July 2002
Elevation (m)
Distance (m)
100.0
99.5
99.0
98.5
98.0
0.0
2.0
4.0
6.0
8.0
10.0


b
Woody debris
Cross-section 21 July 02
Cross-section 20 September 02
Water level 7 July 02
Bottom of woody debris
Elevation (m)
Distance (m)
100.5
100.0
99.5
99.0
98.5
98.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0

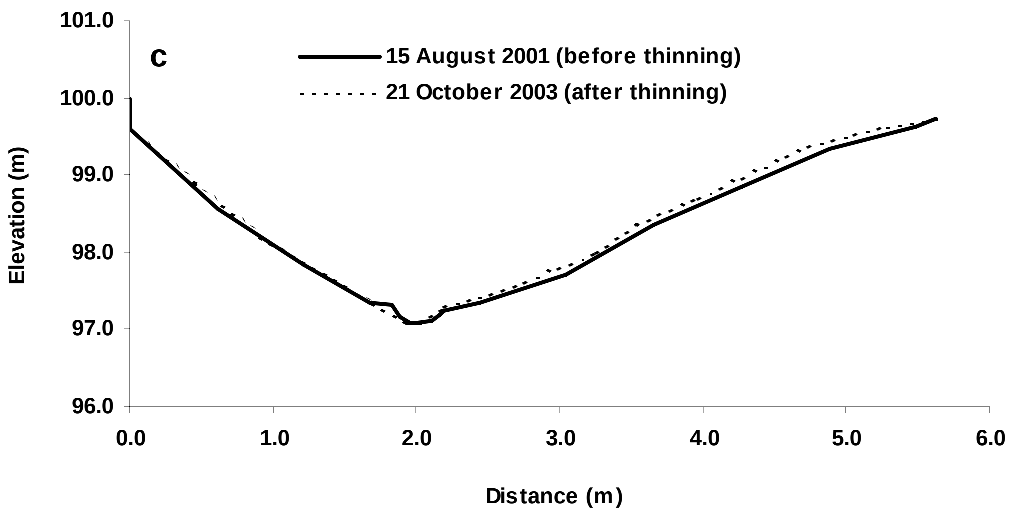
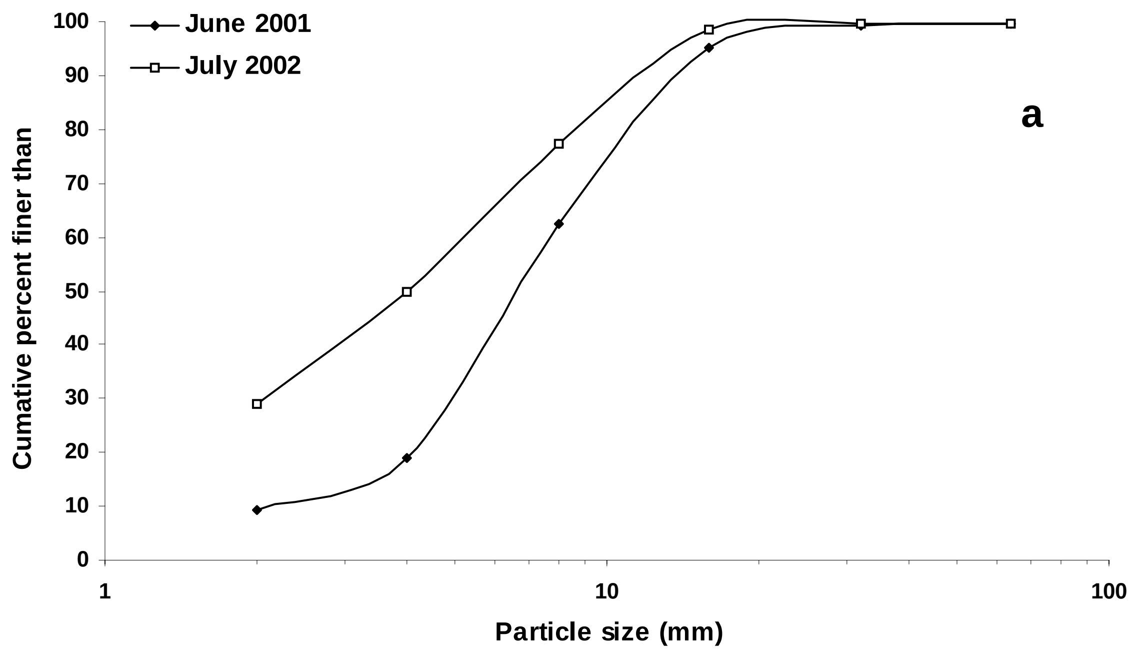


Figure 24. Channel cross-section over time in: (a) Saloon Gulch, (b) Brush Creek, and (c) No Name Creek.

Figure 25. Percent of the bed material finer than 8 mm in 2001 and in 2002 after the Hayman wildfire in Saloon Gulch and Brush Creek.

Figure 26. Percent of banks classified as eroding in 2001 and in 2002 after the Hayman wildfire in Saloon Gulch and Brush Creek.



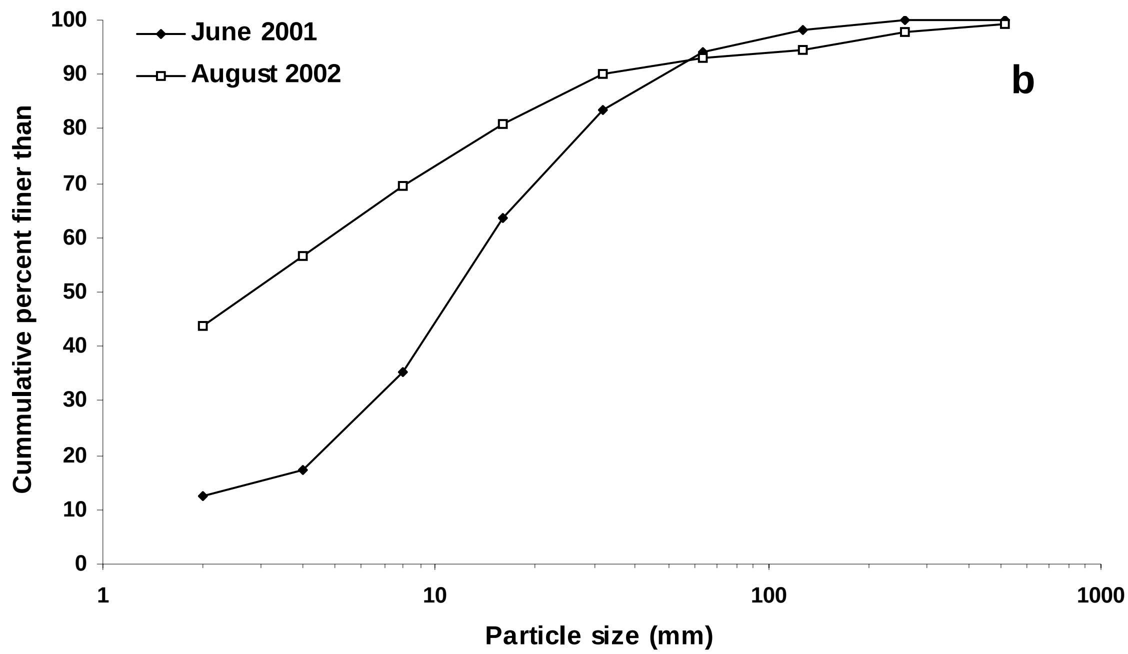


Figure 27. Particle-size distribution in 2001 and in 2002 after the Hayman wildfire in: (a) Saloon Gulch, and (b) Brush Creek.

3.4.2 Runoff and water quality

Eight water samples were taken from both Saloon Gulch and Brush Creek prior to the Hayman fire. At No Name Creek four samples were taken in 2001 and 9 samples in 2002. The mean discharge was only 0.2-0.4 L s^{-1} at Saloon Gulch and No Name Creek and 1.3 L s^{-1} in Brush Creek (Table 14). Conductivity was 170-180 $\mu S\ cm^{-1}$ at all sites, and the sum of anions and the sum of cations was between 1.6 and 1.9 meq L^{-1} at all sites. There were no significant differences between sites for any of the water quality parameters prior to the Hayman fire. Water quality was very good as indicated by the low concentrations of nutrients and suspended solids.

Table 14. Mean values for discharge and selected water quality parameters for the three streams in the study area in 2001 and after the Hayman fire in 2002. Significant differences in mean values are in bold.

	Site					
	Saloon Gulch		Brush Creek		No Name Creek	
Water quality parameter	Pre-fire	Post-fire	Pre-fire	Post-fire	2001	2002
Number of samples	8	1-2*	8	4-6*	4	9
Discharge (L s^{-1})	0.2	0.6	**1.3**	**11.9**	0.3	0.4
pH	7.9	7.8	7.9	7.9	7.8	7.6
Conductivity (μS cm^{-1})	180	400	**170**	**290**	173	193
Potassium (mg L^{-1})	2.9	6.7	**2.8**	**4.7**	4.3	4
Magnesium (mg L^{-1})	4.3	11.6	**4.3**	**7.9**	3.6	4
Calcium (mg L^{-1})	24.9	59.6	**21.1**	**41.8**	22	24
Chloride (mg L^{-1})	1.8	2.5	2.2	2.3	1.4	3.5
Nitrate (mg L^{-1})	0.5	0.3	0.1	0.3	0.2	0.08
Ammonium (mg L^{-1})	0.0	0.3	0.0	0.06	0.0	0.0
Sulfate (mg L^{-1})	17.5	16.9	**0.01**	**0.07**	24.6	31.8
Acid neutralizing capacity (mg L^{-1})	1310	3973	**1095**	**2414**	864	836
Total suspended sediment (mg L^{-1})	10	35	**16**	**4600**	9	7
Turbidity (NTU)	5	17	10	62	5	5
Sum of anions (meq L^{-1})	1.9	4.5	**1.7**	**3.1**	1.6	1.8
Sum of cations (meq L^{-1})	1.9	4.4	**1.7**	**3.1**	1.7	1.9

* Sample size varies by parameter.

Although the number of samples taken after the Hayman fire is limited, the data show a marked increase in discharge and the concentrations of nearly all of the water quality parameters (Table 14). The sum of anions and the sum of cations approximately doubled after the fire, as did the mean concentrations of potassium, magnesium, calcium, and chloride.

In Saloon Gulch the mean acid neutralizing capacity approximately tripled after the fire, but this increase was not significant. In Brush Creek the acid neutralizing capacity doubled after the fire and this increase was significant (p=0.001), because of the greater number of post-fire samples. The concentration of sulfate in Brush Creek increased significantly after the fire (p=0.01), while in Saloon Gulch there was a slight decrease in sulfate after the fire.

Mean nitrate concentrations in Brush Creek after the fire increased from 0.1 to 0.3 mg L^{-1}, while the concentration of ammonium increased only slightly from below the detection limit to 0.3 mg L^{-1}. In Saloon Gulch the mean nitrate concentration decreased from 0.5 to 0.2 mg L^{-1}, and the mean concentration of ammonium decreased from 0.06 to below the detection limit. These changes were highly significant ($p<0.001$) in Brush Creek, while the changes in Saloon Gulch were not significant, probably due to the very limited number of samples taken after the fire.

A sharp increase in ammonium concentrations immediately after the fire was measured in both Brush Creek and Saloon Gulch (Figure 28). At the same time there was a decrease in the nitrate concentration in Brush Creek. In Saloon Gulch the nitrate concentration slightly increased. This and the doubling of the acid neutralizing capacity indicate a significant change in the N_2 mineralization process after the fire as observed elsewhere (Dissmeyer, 2000). The oxidation (burning) of organic matter causes an increase in the ammonium concentrations, and this combined with the increase in the acid neutralizing capacity creates the right conditions for N_2 mineralization. This explains the decreasing nitrate concentrations coinciding with the increase in ammonium concentrations. A complete list of water quality data is in Appendix 15.

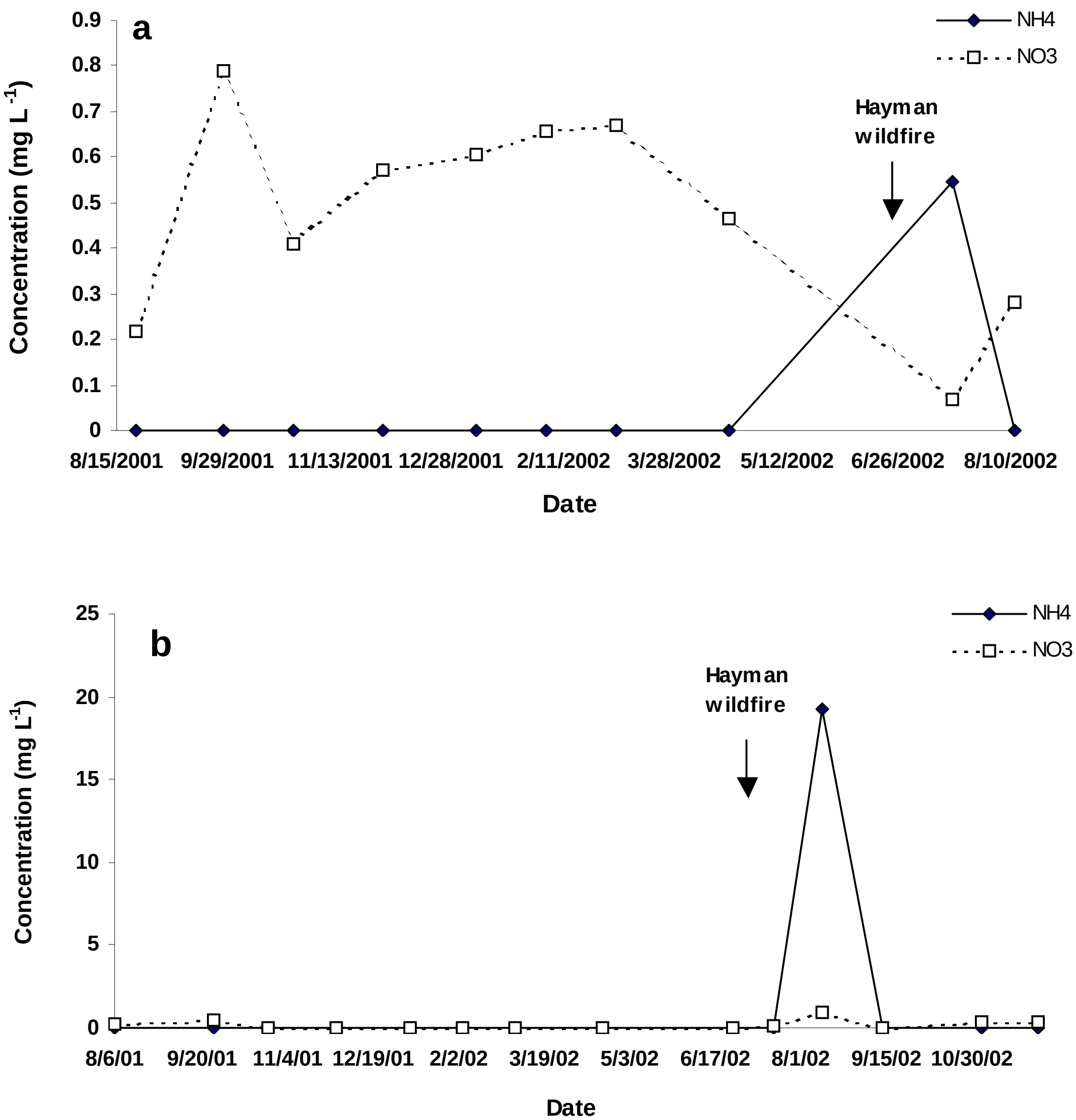


Figure 28. Ammonium and nitrate concentrations over time in: (a) Brush Creek, and (b) Saloon Gulch.

The mean concentration of total suspended solids (TSS) increased after the fire in both Saloon Gulch and Brush Creek, but this increase is difficult to interpret because the concentrations of TSS are so variable in time. The highest measured concentration was 23,000 mg L^{-1} in Brush Creek on 13 September 2002, as this sample was taken after three successive 5-mm storms in the previous four days. The mean turbidity after the fire also increased in both Saloon Gulch and Brush Creek, but the increases were not significant. TSS concentrations were closely related to turbidity ($R^2 = 0.85$; $p<0.0001$) (Figure 29), suggesting that turbidity may be a useful surrogate for estimating TSS.

In the unburned Trumbull catchment there were no significant changes between 2001 and 2002 for discharge or any of the water quality parameters (Table 14). In late October 2002 approximately 50% of the drainage area above the No Name Creek was thinned. This occurred at the end of the summer rainfall season, and just one water quality sample was taken after thinning on 3 December 2002. The water quality parameters from this sample showed no changes compared to the pre-thinning values. Continued water sampling should help indicate whether thinning has any effect on water quality.

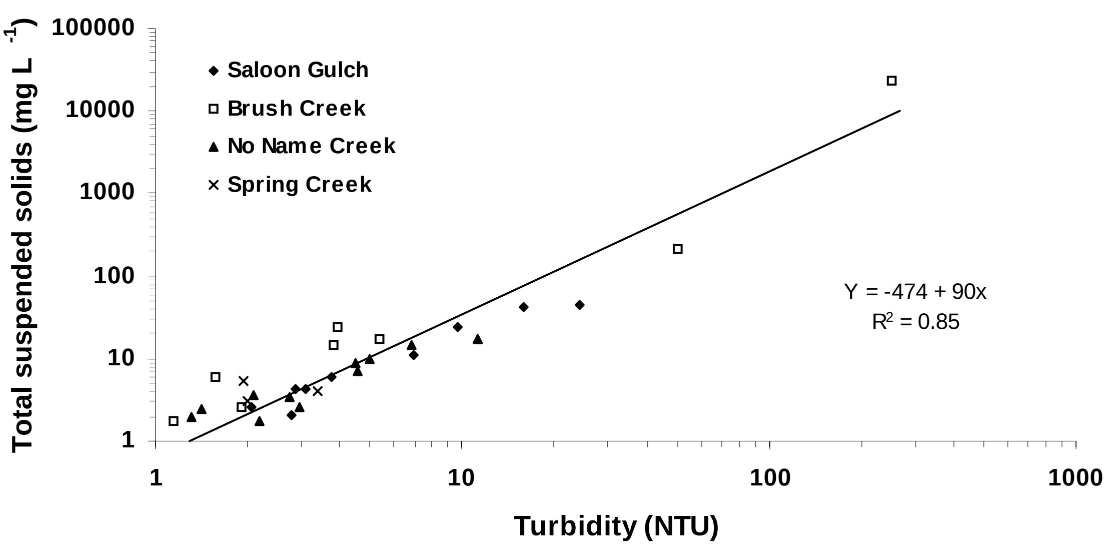


Figure 29. Total suspended solids versus turbidity for Saloon Gulch, Brush Creek, No Name Creek, and Spring Creek.

4. DISCUSSION

4.1 Sediment production from paired swales

4.1.1. Effects of thinning

In 2001 only 3 of the 20 swales in Trumbull produced any sediment. The average erosion rate from these three swales was 0.66 kg m^{-2}. Since the other 17 fences did not produce any sediment the overall mean erosion rate was 0.12 g m^{-2}. The three Trumbull swales that produced sediment were all on south-facing slopes, had a mean percent bare soil of 37%, unusually shallow soils, and bare areas that drained directly into the sediment fences. In contrast, the mean percent bare soil on the 17 swales that did not produce any sediment was only 15%. In 2002 none of the swales in Trumbull produced any sediment, nor did the swales in upper Saloon Gulch or Spring Creek prior to the Hayman fire.

The amount of ground cover is important because this protects the soil from the kinetic energy of raindrops (Osborn, 1953) and provides resistance to surface runoff. Wright at al. (1982) found that 60% to 80% ground cover provided effective protection from surface erosion. In Arizona thinning did not cause a measurable increase in sediment yields despite the observed ground disturbance and compaction (Ffolliott, 1975). The thinning in Trumbull is not expected to cause any erosion, as nearly 80% of the ground surface after thinning was covered with litter, chips, downed wood, and live vegetation (Table 3).

The effects of thinning on sediment yields may vary with storm size and intensity. A rainstorm with an estimated recurrence interval of 100-150 years doubled the sediment yield from a ponderosa pine watershed in Arizona that had been thinned (Ffolliott, 1975). The thinning in Trumbull took place in early fall 2002, which is after the summer storms that are responsible for most of the erosion in the study area. In summer 2003, there were no large rainstorms events and none of the thinned swales produced any sediment (E. Brown, Colorado State University, pers. comm., 2004). The limited amount of ground disturbance suggests that the thinned swales are unlikely to produce large amounts of sediment, but the effect of exceptionally large storm events on erosion rates is not known. At the Manitou Experimental Forest rainfall simulations with an intensity of 50-100 mm hr^{-1} caused 1-4 kg m^{-2} of erosion on plots with nearly 75% litter and vegetation cover (Gary, 1975). In the unburned swales at Spring Creek, a 35-minute storm of 28 mm did not generate any sediment.

The preliminary results from Trumbull cannot be readily extrapolated to the entire range of conditions in the South Platte River watershed. Elevations at Trumbull are relatively low and the rainfall data suggest that the Trumbull area is drier than the other study sites. As the thinning extends to higher elevations, rainfall erosivity will increase and this will increase the erosion risk. Study sites should be established at higher elevations to better assess the effects of thinning on runoff and erosion rates.

4.1.2. Effects of the Hayman wildfire

After the Hayman fire the mean percent ground cover decreased from 90% to 6%. Burning the surface litter and vegetation led to the development of a water repellent layer and exposed the soil surface to rainsplash. After the fire, an 11.2-mm rainstorm with a calculated erosivity of 136 MJ mm ha^{-1} hr^{-1} generated a mean erosion rate of 0.75 kg m^{-2}. This value is similar to the erosion rate observed in other severely-burned areas in the Colorado Front Range (Benavides-Solorio, 2003). This rain event had a recurrence interval of about one year, and the calculated erosivity is less than half of the estimated mean annual erosivity (Renard et al., 1997). Larger and more intense storms can be expected to result in much higher erosion rates. After the Buffalo Creek fire the estimated erosion rate from a rainstorm with an intensity of 90 mm hr^{-1} was 7.6 kg m^{-2} (Moody and Martin, 2001a), or about ten times the value measured in upper Saloon Gulch.

Mean erosion rates from three subsequent storms were less than 0.01 kg m^{-2}, but approximately 2400 kg of sediment and ash was collected from the sediment fences. The amount of rain in these three storms varied from 4.8 to 23.0 mm, but the rainfall intensity was only 3 mm hr^{-1} and the maximum erosivity was 16.4 MJ mm ha^{-1} hr^{-1}. These results show that relatively small storms can generate measurable erosion from areas that burned at high severity.

After the fire the crest gauges recorded peak water levels of up to 28 cm, indicating a shift in the dominant runoff process from subsurface stormflow to Horton overland flow. This overland flow initiated extensive rilling in the swales burned at high severity. This rill incision is believed to be a larger source of sediment than the erosion on the adjacent hillslopes (Moody and Martin, 2001a; Pietraszek and MacDonald., 2003).

On average, the eroded sediment from the swales in Upper Saloon Gulch had 10% less coarse material and 37% more silt than the surface soils. These differences were significant, indicating that there was preferential erosion and transport of the silt-sized fraction. This is in agreement with the results from Benavides-Solorio (2003), who found that the sediment eroded from severely-burned areas had 25% more silt than the surface soils.

Sediment from the hillslopes, rills, and channel was transported downstream and deposited in lower-gradient reaches. The Saloon Gulch flume was completely buried by sediment and the flume in Brush Creek was partially or completely filled with sediment after every 5-mm rainstorm. Similarly, after the Buffalo Creek fire up to 0.5 m of sediment was deposited in Spring Creek (Moody and Martin, 2001a). The increase in runoff and sediment loads increased the proportion of eroding banks in the two study reaches by 5 to 8 times after the fire, and this will further increase the amount of sediment available to streams. The net result was the development of a new alluvial fan at the mouth of Saloon Gulch that was 20-30 m wide and 0.5-1 m thick. This fan extended into the South Platte River and confirms that large amounts of sediment are being delivered from the burned areas to the South Platte River. The inputs of fine gravel, sand, silt, and ash have adversely affected water quality and aquatic habitat in the South Platte River (R.Wiley, Denver Water, pers. comm., 2003).

The major controls on post-fire erosion rates at the hillslope scale are rainfall erosivity and percent bare soil (Benavides-Solorios, 2003). The mean percent bare soil for the swales burned at high severity in Upper Saloon Gulch was 94%. The amount of bare soil will decrease over time, but studies in the Colorado Front Range indicate that the percent bare soil must be below about 35% before erosion rates approach background levels (Benavides-Solorios, 2003). Sites burned at high severity still have 40% to 80% bare soil in the second year after burning (Benavides-Solorios, 2003), so high erosion rates can be expected at least through summer 2003.

Since thinning did not greatly decrease the amount of ground cover, thinning is unlikely to cause much of an increase in runoff and erosion rates relative to wildfires. The results of this study indicate that thinning is a better alternative, at least with respect to runoff and erosion, than not thinning and running the risk of a high-severity wildfire.

4.2. Sediment production from roads

Unpaved roads often are the major source of surface erosion in forested areas (Luce and Black, 1999; MacDonald et al., 2001; Ziegler et al., 2000), and the data presented here support this finding. In 2001 the mean sediment production rate from the active surface of the unpaved roads was 2.1 kg m^{-2}, even though the monitoring began in July 2001 or well into the summer storm season. In 2002 the mean road surface erosion rate was only 0.5 kg m^{-2}, and the lower erosion rate in 2002 can be attributed to drier than normal conditions and lower rainfall erosivities.

Reported road erosion rates vary from 0.08 to 15 kg m^{-2} yr^{-1} (Reid and Dune, 1984; MacDonald et al., 2001; Fransen et al., 2001; Luce and Black 2001b). The higher values are from areas with a mean annual rainfall of 900 to 1500 mm as compared to about 180 mm in the study area. The highest summer precipitation observed during this study was 176 mm for the upper Saloon Gulch rain gauge in 2002.

Rainfall erosivity is an important control on road erosion rates. The storm on 31 July 2001 had a calculated erosivity of 350 MJ mm ha^{-1} hr^{-1} and the resulting mean road surface erosion rate was 2.9 kg m^{-2} for the Spring Creek road. Since the estimated mean annual erosivity for the study area is 340 MJ mm ha^{-1} yr^{-1} (Renard et. al., 1997), the expected road erosion rate in an average year should be around 3 kg m^{-2}. In 2002 the mean erosivity from May to October was only 52 MJ mm ha^{-1} yr^{-1} or 15% of normal, and the mean erosion rate was only 0.5 kg m^{-2}. If this erosion rate per unit erosivity is adjusted to the mean annual erosivity of 340 MJ mm ha^{-1} yr^{-1}, the resulting erosion rate is about 3.2 kg m^{-2} yr^{-1}. This is comparable with the measured erosion rate when the rainfall erosivity was close to the annual average. Proportionally higher erosion rates can be expected from more extreme storms and in years with above-average erosivity.

Percent bare soil was an important controlling variable on sediment production when the road erosion data were normalized by storm depth or storm erosivity. An increase in traffic due to thinning will reduce the vegetative cover and probably increase road surface erosion. The Trumbull area was thinned in fall 2002, and 45% of the total traffic load in 2002 occurred between September and October. In Spring Creek 84% of the traffic occurred during the period of Christmas tree sales when the road surface was probably frozen or covered with snow. As a result the higher traffic volumes on the Spring Creek road may have less effect on the active road surface and the amount of road surface erosion.

The measured mean annual sediment production rate of 1.3 kg m^{-2} from the active road surface converts to just over 3 Mg per kilometer for a 2.5-m wide road, or nearly

8 Mg km^{-1} yr^{-1} if a mean erosion rate of 3 kg m^{-2} is assumed. The application of these values to all roads in the study area may not be valid since the mean slope of the road segments with fences was 1-3% greater than the mean slope of the roads that were surveyed. The applicability of this sediment production rate also will depend on the amount of traffic and ground cover.

The amount of traffic on the roads in our study area is considered light relative to roads with unrestricted public access. Most of the traffic in this study consisted of light vehicles rather than logging trucks. The mean sediment production rate from the roads in this study is surprisingly similar to the estimated value of 3.8 Mg km^{-1} $yr^{-1}$for roads in the Olympic peninsula subjected to light traffic loads (Reid and Dunne, 1984). This difference could be due to the differences in precipitation and the type of vehicles. The sediment production rate was projected to increase by two orders of magnitude when these roads were subjected to a much higher traffic load of heavy logging trucks (Reid and Dune, 1984). More work is needed to determine the effect of traffic loads and vehicle weights on road erosion rates in the Colorado Front Range.

Surface rills 10-20 cm deep were present on all of the road segments in Trumbull. Comparable rills were present along 56% of the roads in Spring Creek and 32% of the roads in upper Saloon Gulch. The greater frequency of rills along the Trumbull road may be attributed to the steeper and longer road segments in Trumbull as compared to the road segments in Spring Creek and upper Saloon Gulch. The road segments with sediment fences were representative of the entire road network with respect to their length, but they were slightly steeper than the surveyed road segments. The implication is that road segments with sediment fences may have more rilling than average and higher erosion rates. More detailed measurements of rills on the road surface can provide a better understanding of road erosion processes and the relative contribution of rills to sediment production rates.

The eroded sediment had significantly more silt and a smaller proportion of both coarse particles and sand than the road surface. The eroded sediment from the swales also had more silt and less sand than the surface soils. These results show that preferential erosion and transport of the finer particles occur at both the hillslope scale and from the road surfaces. In larger storms with more erosivity the eroded sediment tends to be more representative of the particle-size distribution of the eroding surface. This shift in the particle-size distribution of the eroded sediment with increasing erosivity could be associated with a shift in the dominant erosion process from sheetwash to rill erosion.

4.3. Road connectivity and sediment delivery to the stream network

The effect of roads on streams depends upon the extent to which the road network is connected to the stream network (McCashion and Rice, 1983; Wemple et al., 1996). A study in Oregon found that 57% of the total road length was connected to streams (Wemple et al., 1996). Roads increased the drainage density by 21% to 50%, and this should increase the amount of road-derived sediment that reaches the stream network (Wemple et al., 1996).

Road position on the hillslope affects both the proximity of the road to the stream and the amount of subsurface flow that is transformed to overland flow. La Marche and Lettenmaier (2001) found that the distance between the relief culvert and the channel was one of the most significant variables in controlling the connectivity of roads to the stream network. The interception of subsurface flow will increase runoff rates and potentially the amount of sediment delivered to the streams (Bowling and Lettenmaier, 2001). A study in Australia found that relief culverts in mid-slope locations accounted for majority of the road segments that were connected to the streams (Croke and Mockler, 2001).

Seventy percent of the total road length in Trumbull was directly connected to the intermittent channel network, and 80% of this road was considered mid-slope. These results are consistent with findings from other studies. The importance of slope position is further supported by the fact that over 90% of the Spring Creek and Saloon Gulch roads were on ridgetops, but less than 20% of these roads were directly connected to the channel network.

The proportion of the road sediment delivered to the stream also will depend on the particle-size distribution of the eroded sediment (Duncan et al., 1987). About 80% of the sediment eroded from the roads in our study area was gravel and sand. Only 18% was silt and 2% was clay. In western Washington road segments drained by culverts delivered at least 50% of the silt eroded from the roads to the stream, but less than 10% of the sands (Duncan et al., 1987). If 50% of the silt and clay and 10% of the sand eroded from the road surface can be delivered to the channels, and given the connectivity values and road dimensions in Table 7, approximately 1.5-3.5 Mg yr^{-1} of road-derived sediment is being delivered to the channels that drain to the South Platte River. This estimate should be interpreted with caution, as the proportion of road sediment delivered to streams and downstream locations may be lower in the study area than in western Washington due to the lower amounts of precipitation and runoff.

The area of the surveyed roads was less than 0.1% of the total area in each watershed. Field observations indicated that there might be twice as many old roads and skid trails as the actively-used roads included in the road survey. Since these unused roads generally had good litter and vegetative cover, they probably are not contributing large amounts of sediment at the catchment scale. A more careful survey of these old roads and skid trails and the construction of a few sediment fences could indicate whether these sites are an important sediment source.

The average road erosion rate from the road segments over the study period was 1.3 kg m^{-2} yr^{-1}. Assuming a road width of 2.5 m, this converts to over 3 Mg km^{-1} yr^{-1}. Since the average road density is 1.5 km km^{-2}, this road erosion rate converts to nearly 5 Mg km^{-2} yr^{-1}. Using a mean annual erosion rate of 3 kg m^{-2} increases the latter value to 11 Mg km^{-2} yr^{-1}.

The average erosion rate from the severely-burned areas in the Hayman fire in 2002 was 0.71 kg m^{-2} or just over 50% of the measured erosion rate from unpaved roads. However, roughly 50% of the 6.2 km^2 Brush Creek and 3.4 km^2 Saloon Gulch catchments burned at high severity. Applying the measured erosion rate in 2002 to the severely-burned areas, the mean post-fire erosion rate in the first summer after burning for both the Brush Creek and Saloon Gulch catchments was approximately 350 Mg km^{-2}. This indicates that the amount of fire-related sediment in the first year after burning is nearly three orders of magnitude larger than the estimated mean annual sediment production rate from roads. The mean annual sediment production rate from the Trumbull swales prior to thinning was 0.06 kg m^{-2} or 6 Mg km^{-2} yr^{-1}. This value is almost two orders of magnitude lower than the sediment production rate from areas burned at high severity, but there is considerable uncertainty with respect to the mean annual sediment production rate from unburned swales given the large site-to-site and interannual variability.

The relative contribution of roads, fires, and thinning to the total sediment production rate at the catchment scale will vary with time. In summer 2003 the sediment production rates from the areas burned at high severity were similar to 2002 (J. Pietraszek, Colorado State University, pers. comm., 2004). However, sediment production rates from severely-burned areas decrease with time as the vegetation recovers. Post-fire erosion rates in the Colorado Front Range recover to approximately background levels after 3-4 years (Benavides-Solorio, 2003). On the other hand, roads continue to produce sediment, although the amount will vary with road use, climatic conditions, and other factors.

The long-term sediment production rates from roads versus fires will depend on the recurrence interval of high-severity fires and the probability of large storm events in the first 2-3 years after burning. Charcoal dating suggests a recurrence interval of 900 to 1000 years for a large fire and erosion event in the Buffalo Creek area (Elliot and Parker, 2001). If the intervening fires are assumed to produce no sediment, the total sediment production from one fire and storm sequence might approach 2000 Mg km^{-2} if the entire area was burned at high severity. If the long-term mean road erosion rates is assumed to be 3 kg m^{-2} yr^{-1}, sediment production from roads over a thousand year period would be over 10,000 Mg km^{-2}, or roughly five times the sediment production from a high-severity fire. Substantially more sediment could be generated if a fire is followed by an exceptionally large storm event, as happened at Buffalo Creek (Moody and Martin, 2001a)

The relative effect of these sediment sources on water quality and aquatic habitat will depend on the proportion of sediment delivered to the channel network and the size-class distribution of the sediment. The prevalence of surface runoff after a high-severity wildfire suggests that much of the eroded sediment will be delivered to the channel network, while much of the sediment from roads may not be delivered to the channels. Under these conditions fires may deliver more sediment to downstream areas than roads. The timing of the sediment delivery would also differ, as fires produce a large sediment pulse as opposed to the chronic sediment inputs from roads.

4.4. Water quality, runoff, and channel morphology

Wildfires have a profound effect on runoff rates and water quality (Tiedeman et. al., 1978). A total suspended sediment concentration (TSS) of 23,000 mg L^{-1} was measured in Brush Creek after the Hayman fire, and this is 290 times the highest value measured prior to the fire. Higher values almost certainly occurred in Brush Creek and Saloon Gulch, but the sampling in this study consisted of grab samples taken one or two days after a storm event. Kunze (2003) used a pump sampler to obtain a maximum TSS of 41,800 mg L^{-1} after the Bobcat fire southwest of Fort Collins.

Turbidity and TSS concentrations were strongly related. Since turbidity is more easily measured in the field and can be continuously recorded, this relationship could be used to predict TSS concentrations and calculate suspended sediment loads.

Field observations indicated that high ash loads were present in Brush Creek for three or four days after the larger rainstorms. Large deposits of ash were observed in Brush Creek, Saloon Gulch, and the South Platte River. These observations and the water quality data indicate a significant decline in water quality after the fire. The decline in water quality also affected the aquatic life, as dead fish were observed in the South Platte River after several storms in summer 2002.

The mean TSS concentration in No Name Creek in the Trumbull area was only 7-9 mg L^{-1}. TSS and nutrient concentrations in No Name Creek did not change during the 2001-2002 monitoring period. Thinning ponderosa pine forests in Arizona caused no detectable change in the concentrations of suspended sediment, calcium, sodium, iron, phosphorus, or nitrate (Brown et al., 1974, Ffolliott, 1975). Since the thinning did not produce any measurable surface runoff or erosion in 2003 (E. Brown, Colorado State University, pers. comm., 2004), thinning is unlikely to cause any adverse changes in water quality.

Studies in the Colorado Front Range have indicated that runoff and erosion can increase by several orders of magnitude from areas burned at high severity (Moody and Martin, 2001a,b; Benavides-Solorio, 2003; Kunze, 2003). After the Buffalo Creek fire unit-area peak discharges were up to 24 $m^3 s^{-1} km^{-2}$ (Moody and Martin 2001a). A sharp ash line in Brush Creek indicated a peak water level of 1.4 m above the bottom of the channel from the storm on 7 July 2002. Using the slope-area method and a Manning's n of 0.07, the peak flow was estimated to be 43 $m^3 s^{-1}$. This converts to a unit area discharge of nearly 7 $m^3 s^{-1} km^{-2}$, or 28% of the largest peak flow estimated by Moody and Martin (2001a) after the Buffalo Creek fire.

The lower peak discharge in Brush Creek is probably due to the lower rainfall intensity. The maximum 30-minute rainfall intensity for the storm that generated this peak discharge was only 15 mm h^{-1}, while the estimated storm intensity for the large peak flow after the Buffalo Creek fire was 90 mm h^{-1} (Moody and Martin 2001a).

The increase in runoff after the fire caused extensive rilling in the swales. Exposed bedrock was observed in the steeper portions of both Brush Creek and Saloon Gulch, indicating channel scour. Extensive aggradation was observed in Saloon Gulch and Brush Creek where gradients were less than 2%. The Brush Creek flume was filled with sediment and debris after rain events as small as 5 mm. After the 12.4-mm storm on 6 July 2002, sediment blocked the culvert that connects Brush Creek with the South Platte River. The existing culvert was replaced with a bigger one to accommodate the higher peak flows and sediment loads. An alluvial fan 20-30 m wide and 0.5-1 m thick developed at the mouth of Saloon Gulch, indicating that large amounts of sediment were being delivered to the South Platte River.

The sediment deposition observed in Saloon Gulch and Brush Creek was comparable to the mean value of 0.5 m in Spring Creek after the Buffalo Creek fire (Moody and Martin 2001a). Channel aggradation and degradation will continue, with the relative balance depending on the amount of runoff relative to the sediment inputs. For example, the cross-section survey in Saloon Gulch on 20 September 2002 showed approximately 0.2 m of channel incision, while the cross-section survey on the same date in Brush Creek indicated up to 0.3 m of new sediment deposits.

Sediment inputs into the channel will rapidly decrease as runoff and erosion rates return to near-background levels. This will allow the streams to begin incising and transporting the accumulated sediments. The reduction in peak flows with vegetative regrowth will progressively reduce the ability of the streams to entrain and transport the sediment already in the channels. The implication is that sediment delivery to downstream areas is likely to remain elevated for some time after hillslope erosion rates have recovered to near-background levels.

5. CONCLUSIONS

Forty-one sediment fences were established in summer 2001 to measure sediment production from zero- or first-order basins in three study areas near Deckers, Colorado. The contributing areas ranged from 340 to 9800 m^2 and the mean slope was 23%. Soils were classified as gravelly coarse sandy loam.

All of the erosion in the study area occurred from summer rainfall events. From 8 August to 31 October 2001, the average rainfall in the three study sites was 89 mm. From 1 May to 31 October 2002 the average rainfall was 124 mm. On average the Trumbull site received only 65% as much precipitation as Spring Creek. Precipitation over the same periods at the nearest long-term station was 40% of normal in 2001 and 50% of normal in 2002.

In 2001 and before the Hayman fire in 2002, none of the 24 swales in upper Saloon Gulch and Spring Creek produced any sediment. Less than 10% of the ground cover was classified as bare soil. After the Hayman fire, bare soil and ash accounted for approximately 90% of the ground cover. Soils were water repellent at the surface in both unburned and burned sites. Soil water repellency decreased with depth and the burned sites were significantly more water repellent at 0 and 3 cm than the unburned sites.

After the Hayman fire, the average erosion rate from an 11.2-mm rain storm on 21 July 2002 was 0.75 kg m^{-2}. Sediment production rates from three subsequent storms were less than 0.01 kg m^{-2}. While the amount of rainfall for these three storms varied from 4.8 to 23.0 mm, the maximum rainfall intensity was only 3 mm hr^{-1} as compared to 62 mm hr^{-1} for the storm on 21 July 2002.

Swale area explained 80% of the variability in sediment production in the burned swales. This relationship was not improved by the addition of storm depth or storm erosivity, as 95% of the sediment was generated by the storm on 21 July. Storms in summer 2002 generally had a recurrence interval of less than one year and the total erosivity was approximately one-half of the estimated mean annual erosivity. Substantially higher erosion rates could be expected from larger and more intense rain events. Erosion rates in the second and third years after the fire will depend primarily on the size and intensity of the summer rain storms and the recovery of ground cover.

Eighty percent of the sediment eroded from Upper Saloon Gulch was coarse particles and sand, but there was significantly more sand, silt, and organic matter in the eroded sediment than in the surface soils. Higher-intensity rain storms yielded a significantly higher proportion of coarse particles. This indicates selective detachment and transport of the finer particles.

Mechanical thinning at Trumbull increased the mean percent of litter and downed wood from 70% to 82% and decreased the amount of live vegetation on the ground surface from 10% to 6%. The percent of bare soil remained largely unchanged at 20%.

In 2001 only three of the 20 swales in Trumbull produced any sediment, and the overall mean erosion rate was 0.12 kg m^{-2}. In 2002 Trumbull received 117 mm of summer precipitation and the highest rainfall intensity was 8.1 mm hr^{-1}. None of the swales in Trumbull produced any sediment in 2002. Thinning is not expected to increase erosion rates because the proportion of bare soil was unchanged. Data from the Manitou Experimental Forest suggest that storm events larger than 25 mm hr^{-1} can initiate surface runoff. At Trumbull the largest rainstorm measured only 9.1 mm and the maximum 30-minute intensity was 12.2 mm hr^{-1}. Unfortunately, rainfall data are not available for the sediment-producing storm in 2001.

Twenty-one sediment fences were installed on road segments to measure sediment production from unpaved forest roads. Road segment length varied from 22 to 219 m and active width varied from 2.1 to 3.9 m. The mean slope was 8% and slopes for individual segments varied from 6 to 16%.

The mean sediment production rate from the active road surface was 2.1 kg m^{-2} in 2001 and 0.5 kg m^{-2} in 2002. The mean percent bare soil on these segments increased from 78% in 2001 to 93% in 2002. Seventy percent of the sediment produced in 2001 resulted from one storm with 27.3 mm of rainfall and an erosivity of 350 MJ mm ha^{-1} hr^{-1}. In 2002 the total erosivity from May to October was only 52 MJ mm ha^{-1} yr^{-1}, or 16% of the value in 2001. Active road surface area explained 34% of the variability in sediment production, and the product of road area times slope explained only slightly more of the variability than active road area. Percent bare soil explained 73% of the variability in sediment production at the road segment scale when sediment production was normalized by storm depth or erosivity. The eroded sediment had significantly less sand and significantly more silt and clay than the road surface. As in the case of the swales, the proportion of coarse particles increased with increasing storm erosivity.

A survey of 13.5 km of roads identified 204 discrete segments. Only 18% of the segments had rills or sediment plumes that extended for more than 10 m. Active road area times slope explained 43% of the variability in rill length and 56% of the variability in sediment plume length. Segments with larger rills were more likely to be connected to the stream channel. More than 90% of the roads in upper Saloon Gulch and Spring Creek are on ridgetops, and less than 20% of the roads in these areas are connected to the stream network. In contrast, 80% of the roads in Trumbull were in a midslope position. The combination of slope position, steeper roads and sideslope gradients, and longer segment lengths meant that 70% of the roads in Trumbull were connected to the stream. Constructing roads on ridgetops and shortening the segment length could reduce sediment production and sediment delivery to the stream network.

Three channels were surveyed in 2001 in catchments ranging from 3.3 to 6.2 km^2. The estimated bankfull channels were all less than a meter wide and only 5 to 12 cm deep. Less than 30% of the banks were eroding. After the Hayman fire, the high water marks were up to 1.4 m above the estimated bankfull stage. A 14-mm storm generated estimated peak flows of 6.9 $m^3\ sec^{-1}\ km^{-2}$. The high runoff and erosion rates after the Hayman fire caused resulted in degradation in the steeper reaches and up to 1.3 m of aggradation in reaches with gradients less than 2%. The percent of eroding banks increased from by 5 to 8 times. The percent of particles less than 8 mm increased from 35% to 70% in Brush Creek and from 62% to 70% in Saloon Gulch.

Limited water quality sampling after the Hayman fire showed large increases in total suspended solids in Saloon Gulch and a 3-fold increase in Brush Creek. Turbidity explained 85% of the variability in total suspended sediment and can be used to predict suspended sediment concentrations. Nutrient concentrations, the sum of anions, and the sum of cations all approximately doubled after the fire. The oxidation (burning) of organic matter caused an increase in ammonium concentrations, and nitrogen mineralization increased as a result of the increase in ammonium and acid neutralizing capacity.

These results show that the Hayman fire had a profound effect on runoff, erosion, channel morphology, and water quality. The reduction in percent bare soil over time should greatly reduce runoff and erosion rates and improve water quality. The effects of the Hayman fire on channel morphology will continue longer, as the decreasing runoff will have less energy to remove the large amounts of sediment deposited in the channels. Thinning is expected to have little effect on runoff and erosion rates except in the largest storm events. Under unburned conditions unpaved roads are a large and chronic sediment source. The effects of roads on downstream areas can be minimized by locating the roads on ridgetops and ensuring frequent, dispersed drainage through outsloping or other practices.

6. RECOMMENDATIONS

All of the erosion observed in the study area results from summer convective storms. The tremendous spatial variability of these storms indicates that a higher density of rain gauges is needed to adequately capture the rainfall inputs to each study site.

Ground cover is one of the major controls on hillslope erosion rates. Ground cover and sediment production should be regularly monitored in the severely-burned swales to assess recovery over time.

Thinning did not change the amount of bare soil, but there was ground disturbance from the equipment. The amount of ground disturbance and effects of thinning on compaction should be measured in order to determine whether these factors affect runoff and erosion rates.

The thinned swales are at a low elevation within the study area and appear to receive less rainfall than the other study sites. Sediment fences need to be installed at higher elevations and on steeper slopes to better assess the effects of thinning on surface erosion rates. The establishment of more sites will increase the likelihood of experiencing a large storm event. Monitoring of channels should continue in order to evaluate the effects of thinning at the watershed scale, particularly for storms with higher recurrence intervals.

Field observations showed extensive rill development on the roads and in the swales that burned at high severity. Detailed rill surveys should be conducted to determine the contribution of rills to sediment production.

Field observations revealed the presence of numerous old forest roads and skid trails. Sediment fences should be installed to measure sediment production rates relative to actively-used roads. If these old roads and skid trails are actively eroding, they should be surveyed to determine their density and connectivity with the stream network.

Field observations of Brush Creek and Saloon Gulch indicated areas of scour and sediment deposition. More channel cross-sections should be established along Brush Creek and Saloon Gulch to document the changes in scour and deposition over time. These surveys, together with the hillslope-scale data on rill and swale erosion, should help quantify the relative importance of each sediment source to the channel network and to sediment yields at the catchment scale.

The frequency of water sampling should be increased, especially during the summer season when the majority of convective storms occur. A new control catchment should be established to provide baseline channel morphology and water quality data. These data can serve as a benchmark for comparisons against the thinned and burned catchments.

The Brush Creek flume should be cleaned out after storms. A debris-holding structure upstream of the Brush Creek flume should be installed to improve the functionality of the flume. Smaller flumes should be installed to measure discharge at Trumbull or one of the new thinning sites.

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