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Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and erosion mitigation treatment in the western United States

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Abstract. Between 1998 and 2002, six sites were established immediately after large wildfires in the western United States to determine the effectiveness of contour-felled log erosion barriers in mitigating post-wildfire runoff and erosion. In each pair of matched, burned, and small watersheds (1–13 ha), one was treated with contour-felled log erosion barriers and one was left untreated as a control. For 4 to 6 post-fire years, runoff and sediment yields were measured and correlated with rain properties. High-intensity rainfall produced most of the measured runoff and sediment yields except in the southern California site, where long-duration rain events produced most of the runoff and erosion. For small rain events (less than the 2-year return period for the 10-min duration), the runoff, peak flows, and sediment yields were lower in the treated watersheds than in the control watersheds, but there was no treatment effect for rain events with larger return periods. Improper installation and degradation over time reduced the effectiveness of contour-felled log erosion barriers. Rainfall characteristics and installation procedures should be carefully considered before choosing contour-felled log erosion barriers for post-fire hillslope stabilisation.

Additional keywords: catchment, LEB, sediment yield, watershed.

Introduction

Wildfire is a natural process in many conifer-dominated ecosystems. After fire, the amount of runoff and peak flow can increase dramatically in burned watersheds causing flooding, debris flows, and high rates of soil loss and sedimentation as exemplified by the flooding within and downstream of the area burned by the 1996 Buffalo Creek Fire, resulting in two fatalities, and subsequent sediment deposition in Strontia Springs Reservoir, a major water supply reservoir for Denver, Colorado (Moody and Martin 2001*b*). Also, increases in the amount of fine sediment in streams and rivers may adversely affect spawning and rearing sites for anadromous and resident fish species and degrade stream and riparian habitat. Therefore, post-fire management strategies including application of treatments to hillslopes, roads, and stream channels are often devised to reduce the risk of increased runoff, erosion, and sediment delivery to protect life, property, infrastructure, and aquatic resources.

Post-wildfire erosion rates, like natural erosion rates, vary by geology, topography, climate, and vegetation as well as by historic land use. Relatively undisturbed forests produce clean runoff, low erosion rates, and low sediment yields (Buckhouse and Gaither 1982; Morris and Moses 1987; Binkley and Brown 1993; MacDonald and Stednick 2003). The reported range of post-wildfire erosion rates is 0.005 to 370 $\text{Mg ha}^{-1}\text{ year}^{-1}$; the low value was calculated from suspended sediment measured in a small watershed burned at moderate severity (Campbell *et al*. 1977), whereas the high value was from measurements using fixed tapes on a steep hillslope burned at high severity (Hendricks and Johnson 1944). Recently, direct measurement of hillslope sediment yields has produced erosion rates of 1.9 to 63 $\text{Mg ha}^{-1}\text{ year}^{-1}$ measured after high severity wildfires (Robichaud and Brown 2000; Robichaud 2005; Robichaud *et al*. 2006; Wagenbrenner *et al*. 2006; Spigel and Robichaud 2007).

Post-fire assessments are used to evaluate the potential for storm damage to natural and human communities immediately after large wildfires in countries such as Australia (State of Victoria 2006), Canada (Pike and Ussery 2006), Greece (Raftoyannis and Spanos 2005), and the United States (USDA Forest Service 1995, 2004). In the United States, post-fire assessment teams estimate the probability associated with runoff events and magnitude of flood flows, erosion, and sediment delivery to determine the risk of damage to downstream resources. If warranted, emergency stabilisation treatments are applied to mitigate these risks. Stabilisation treatments often are designed to reduce hillslope erosion (e.g. mulches and erosion barriers) rather than to store sediment somewhere downstream (e.g. sediment detention basins). One frequently used hillslope stabilisation technique is contour-felled log erosion barriers (LEBs).

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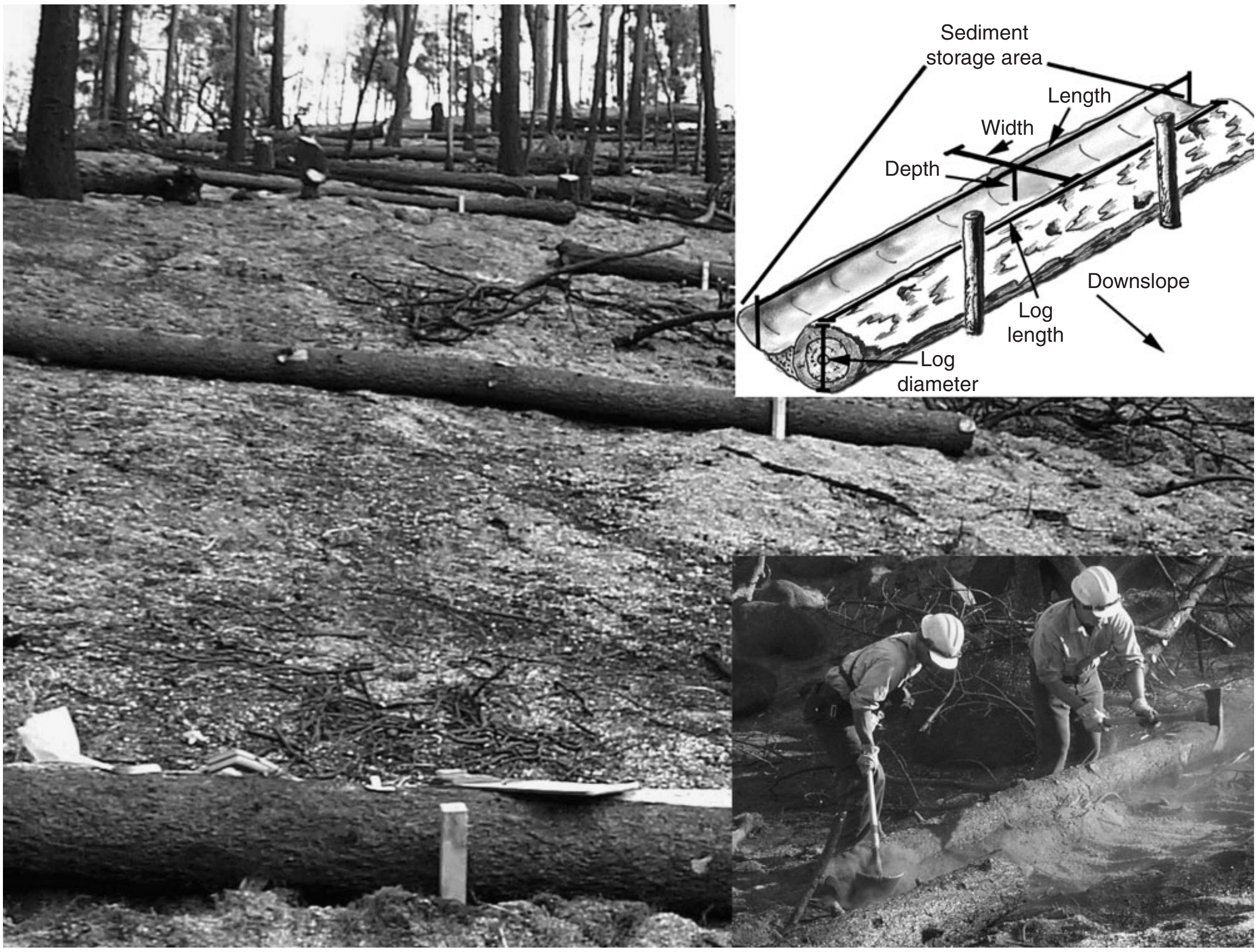

Fig. 1. Contour-felled log erosion barrier (LEB) layout on a hillslope with an inset diagram of measurements made on each log and a photograph of an LEB being installed (from Robichaud *et al*. 2000, 2008).

The standard installation technique consists of felling burned trees and laying them on the ground along the slope contour (USDA Forest Service 2004) (Fig. 1). Each log is anchored in place and gaps between the log and the soil surface are filled with soil to create a storage basin on the upslope side of the log where overland flow is trapped. Earthen berms are sometimes installed at both ends of the basin to reduce the amount of water flowing around the ends of the log. The LEBs are usually laid out in staggered tiers designed to eliminate long uninterrupted flow paths.

LEBs were designed to increase detention and infiltration of overland flow, thereby reducing runoff and sediment transport capacity (Robichaud *et al*. 2005). Robichaud *et al*. (2000) reported survey results of land managers' experiences with LEBs and found that 65% of respondents had 'good' or 'excellent' experiences. Although there are no studies that have compared runoff from LEB-treated sites with untreated sites, Wagenbrenner *et al*. (2006) reported that LEBs increased infiltration, especially in the area upslope of the erosion barrier that was disturbed during installation. Two contour-felled LEB studies (McCammon and Hughes 1980; Miles *et al*. 1989) attempted to quantify treatment effectiveness by estimating the amount of sediment stored behind the erosion barriers; however, they did not measure changes in post-fire runoff, infiltration, or sediment yield. Gartner (2003) examined the effectiveness of LEB treatment at several spatial scales after the 2000 Hi Meadows Fire in Colorado and found that the treatment reduced sediment yields at the hillslope ($400\,m^2$) and watershed (16 ha) scales but not at the sub-watershed (1–5 ha) or plot ($1–5\,m^2$) scales. In a hillslope-scale study, Robichaud *et al*. (2008) found no significant difference in the sediment yields between LEB-treated and control sites. In a hillslope-scale study after the 2000 Bobcat Fire in Colorado, the calculated storage capacity of the LEBs was greater than the sediment produced in an average year (Wagenbrenner *et al*. 2006). However, the volume of sediment stored behind an LEB is generally less than the total available sediment storage capacity and runoff and sediment have been observed going over the top and around the ends of LEBs even when the LEB was less than half-filled (Robichaud *et al*. 2008).

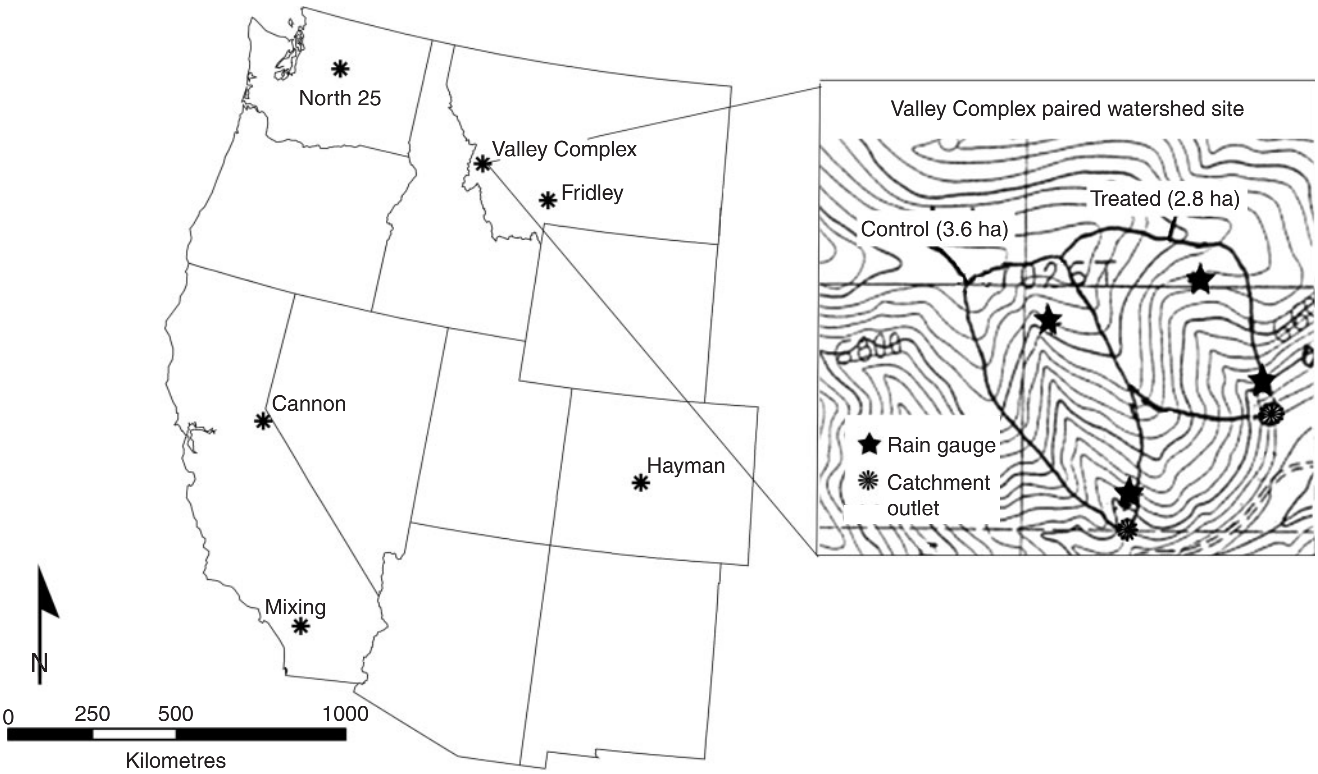

Fig. 2. Location of the six paired watershed study sites in the western USA with a detailed topographic map of the Valley Complex site as an example of a typical site.

The amount of time it takes for burned sites to recover to prefire conditions is not yet well understood. DeBano *et al.* (1996) demonstrated that following a wildfire in ponderosa pine, sediment yields from a low severity fire recovered to normal levels after 3 years, but moderately and severely burned watersheds took 7 and 14 years, respectively. Other post-wildfire recovery studies have indicated that sediment yields generally decrease by an order of magnitude with each year since the fire and recover with no measurable fire-influenced erosion by the 4th or 5th year (Robichaud and Brown 2000; Robichaud *et al.* 2000). However, data on this subject are sparse because of the duration and expense required to measure recovery.

Paired watershed studies have been widely used in the United States since the early 1900s to determine effects of various timber and grazing management practices (Bates and Henry 1928; Forsling 1931). Typically, these experiments evaluated differences in two watersheds of similar size during a pretreatment (calibration) period and for several years after treatment. The calibration period was used to determine how well matched the watersheds were with respect to hydrologic response. To date, there have been few significant reports of paired watershed experiments that include a watershed burned by wildfire (Hoyt and Troxell 1934; Helvey 1980; Scott 1997; Loáiciga *et al.* 2001). As a wildfire 'treatment' is nearly impossible to replicate in a managed setting, no calibration period can be established when using matched watersheds for post-wildfire studies.

The goals of the present study were to evaluate the effectiveness of LEBs at reducing runoff and erosion at the small-watershed scale and to gain insight as to the underlying process(es) that control LEB effectiveness. Specific objectives were to: (1) compare total runoff, peak flows, and sediment yields from treated and untreated small watersheds; (2) determine the relationship between the size of rainfall events and effectiveness of the contour-felled LEBs; (3) measure and characterise the key performance traits of the contour-felled LEBs; and (4) quantify post-fire increases and recovery over time of runoff, peak flow, and sediment yields in western forests.

Methods

We designed and initiated a study in autumn 1998 to measure runoff and sediment yields from matched small (1 to 13 ha) watersheds burned at high severity – one burned watershed was treated with LEBs and the other was left as a burned, untreated control. Between 1998 and 2002, a total of six sites throughout the western United States (North 25, Mixing, Valley Complex, Fridley, Hayman, and Cannon) (Fig. 2) were established immediately after large wildfires. As no prefire or pretreatment runoff, peak flow, or sediment yield data were available, it was assumed that the matched watersheds behaved similarly before treatment.

At each site, the two watersheds were located in close proximity to each other to minimise differences in climate, soils, prefire vegetation, land use, topography (elevation, aspect, and slope), and burn severity (Hewlett 1971) (Table 1). All sites were located in areas of high burn severity as determined by post-fire assessment teams and were protected from other disturbances, such as salvage logging or grazing, for the duration of the study (4 to 6 years).

Trained crews used standard techniques (USDA Forest Service 2004) to install LEBs on each of the treated watersheds within weeks of wildfire containment. In the Valley Complex, Fridley, and Hayman sites, additional loose soil was mounded at each end of the log to form an earthen end berm that angled upslope.

Sediment traps and instrumentation

A sediment trap and control section were installed at the outlet of each watershed (Robichaud and Brown 2003). A galvanised sheet metal head wall was formed on site to fit the channel shape and constructed to contain eroded sediment (Fig. 3). At the North 25 site, a 300-mm H-flume was installed immediately downstream of the sediment trap. At the Mixing, Valley Complex, and Fridley sites, flow was measured with a 450-mm H-flume installed in the top-centre of the metal head wall. At the Hayman and Cannon sites, the control section was a 380-mm 90° V-notch weir cut in the top-centre of the head wall (Fig. 3). A trash rack was installed ∼1 m upstream of each head wall to protect the control section from debris and to make the flow through the control section less turbulent. Each sediment trap was surveyed to determine the maximum storage volume as well as a depth–volume relationship.

A weather station was installed at each site to measure climate and soil conditions. Tipping bucket rain gauges were used to measure rainfall near the outlet and in the uplands of each watershed, except at the Hayman site, where the outlets of the two watersheds shared one rain gauge and there was only one upland gauge until 2004. Water level in each flume or weir was measured using a magnetostrictive linear displacement transducer – a magnetic float along a stainless steel rod (MTS Systems Inc., Cary, NC, USA).[A] The accumulated sediment, snow, or runoff in each sediment trap (except North 25) was measured using an ultrasonic depth sensor (Judd Communications Inc., Salt Lake City, UT, USA).[A] All measurements were made and recorded every 5–10 min except for rainfall, which was continuously measured, and the cumulative rainfall was recorded in 1-min intervals. A solar-charged, battery-powered CR10 data logger (Campbell Scientific Inc., Logan, UT, USA)[A] was used to control the instruments, store the data, and transmit the data via modem to a common server. Events with at least 6 h between rain gauge bucket tips were treated as separate rain storms. For each storm, the total rainfall (mm), duration (min), and 10-min and 30-min maximum rainfall intensities (I_{10} and I_{30}, respectively) were calculated and averaged across all available gauges. Return periods were calculated using a rainfall-frequency atlas (Miller *et al.* 1973; Arkell and Richards 1986; Bonnin *et al.* 2004). Rain storms were classified as 'large' if the return period

Table 1. Fire start date and location, and watershed area, elevation, aspect, and slopes for the six sites
C, control; T, treated with contour-felled log erosion barriers

Site	Fire start date	Location (°N, °W)	Watershed area (ha)		Watershed outlet elevation (m)		Watershed aspect (degrees)		Mean watershed slope (%)		Portion of watershed with slope >30% (%)	
			C	T	C	T	C	T	C	T	C	T
North 25	4 August 1998	Central Washington (47.99, 120.34)	11.3	8.5	1580	1550	120	180	50	39	94	78
Mixing	1 September 1999	South-western California (33.68, 116.73)	1.4	1.2	1620	1610	20	330	19	24	7	8
Valley Complex	31 July 2000	Western Montana (45.91, 114.03)	3.6	2.8	1720	1730	310	301	46	39	88	81
Fridley	19 August 2001	Southern Montana (45.51, 110.78)	13.3	11.8	1930	1950	125	130	43	37	75	82
Hayman	8 June 2002	Central Colorado (39.18, 105.36)	3.0	3.1	2440	2440	98	94	33	27	63	42
Cannon	15 June 2002	East-central California (38.45, 119.47)	12.6	10.9	2230	2220	40	40	38	44	80	92

[A]Trade names are used for the benefit of the reader and do not imply endorsement by the US Department of Agriculture.

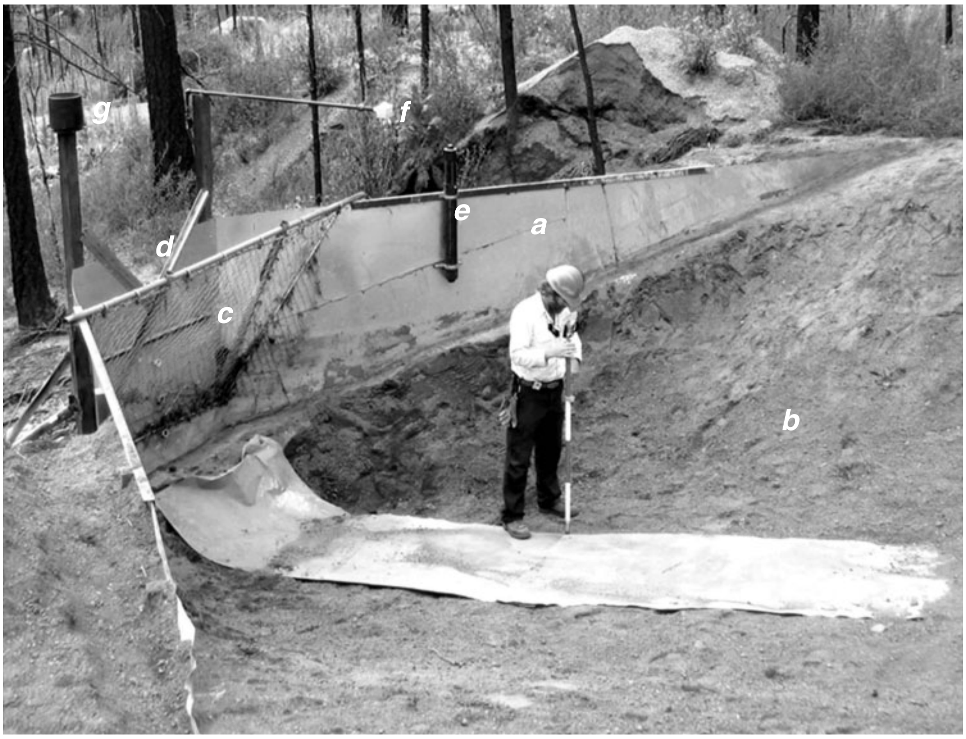

Fig. 3. Typical paired watershed sediment trap and instrumentation: (*a*) sheet metal head wall; (*b*) sediment storage area; (*c*) trash rack; (*d*) V-notch weir; (*e*) magnetostrictive linear displacement transducer (stage sensor); (*f*) ultrasonic depth sensor; (*g*) tipping bucket rain gauge. This photo is from the Hayman site (from Robichaud 2005).

for the 10-min duration was at least 2 years, and 'small' otherwise. The I_{10} (mm h^{-1}) corresponding to the 2-year, 10-min duration was different for each site: 32 at North 25; 48 at Mixing; 31 at Valley Complex; 36 at Fridley; 56 at Hayman; and 43 at Cannon.

Site characterisation

The six sites were located in diverse conifer-dominated ecosystems across the western United States (Table 1). Each small watershed was ephemeral; surface runoff only resulted from rain or snowmelt events. Watershed boundaries were surveyed using a geographical positioning system to determine the area of each watershed, which ranged from 1.2 ha (Mixing) to 13.3 ha (Fridley). The differences in area, elevation, slope, and aspect between the control and the treated watersheds at each site were minimal, with a few exceptions (Table 1).

Four of the sites were located in regions with granitic parent material, whereas two of the soils were volcanic in origin (Table 2). The soils were mostly shallow, gravelly loams, which is typical in the Bitterroot, Sierra Nevada, and Rocky mountain ranges. Soil properties were determined from soil series descriptions, soil maps, on-site soil surveys, and field and laboratory measurements. Bulk densities of the soils ranged from 0.83 to 1.39 g cm^{-3} (Table 2).

A nearby weather station was used to characterise the long-term precipitation for each site, which varied from 400 to 915 mm annually (Table 3). As one might expect, the precipitation amount influenced the vegetation type at each site. Prior to the fires, the drier sites (Mixing, Hayman, Cannon) had pines (Coulter [*Pinus coulteri* D. Don], ponderosa [*P. ponderosa* Laws.], and Jeffrey [*P. jeffreyi* Grev. and Balf.] pines, respectively) as the dominant overstorey vegetation, whereas the wetter sites (North 25, Valley Complex, and Fridley) had grand fir (*Abies grandi* [Douglas] Lindley) or Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) as the dominant overstorey species (Table 3). Similarly, at the dry sites, the prefire understorey consisted of chaparral whitethorn (*Ceanothus leucodermis* E. Greene), common juniper (*Juniperus communis* L.), or sagebrush (*Artemisia tridentate* Nutt. ssp. *vasevana* [Rydb.] Beetle), whereas the wetter sites had ocean spray (*Holodiscus discolor* [Pursh.] Maxim), ninebark (*Physocarpus malvaceus* A. Nelson), or snowberry (*Symphoricarpos albus* S. F. Blake) (Table 3).

To further characterise the LEB-treated watersheds, the number, size, slope, and storage capacity of each LEB was measured before the first sediment-producing storm. The storage capacity of all LEBs at each site was calculated as:

$$V = \sum_{i=1}^{n} L_i d_i w_i (1 - s_i)(1 - c_i) \qquad (1)$$

where V was the total site storage capacity (m^3); n was the number of LEBs at the site; L was the maximum of either the LEB length (Fig. 1) minus 1 m (to account for log taper and reduced storage near the ends of the LEB) or the length of the basin above the LEB (m); d was the mean of three depths of the storage space, as measured from a horizontal line extended from the crest of the LEB to the upslope ground surface (m) (Fig. 1); w was the mean

Table 2. Soil series, textural class, parent material, bulk density, textural fractions, and depth to bedrock for the six study sites

Site	Soil series name(s) [taxonomic class]	Soil textural class	Geologic parent material	Bulk density (0–5-cm depth) (g cm^{-3})	Surface composite sample: Clay fraction (%)	Surface composite sample: Silt fraction (%)	Surface composite sample: Sand fraction (%)	Depth to bedrock (cm)
North 25	Palmich [*ashy-pumiceous, glassy, frigid, Typic Vitrixerands*]	Ashy sandy loam	Volcanic	0.83	1	30	69	150
Mixing	Series name not established [*coarse-loamy, mixed, mesic Typic Xerorthent*]	Loamy sand	Granitic	Not sampled	4	18	78	100 (control); 50 (treated)
Valley Complex	Totelake [*sandy-skeletal, mixed, frigid, Typic Haplustepts*]	Gravelly loam	Granitic colluvium	1.15	4	24	72	>150
Fridley	Series name not established [*loamy, skeletal mixed typic Agriborolls*], [*loamy, skeletal, mixed Mollic Eutroboralfs*]	Gravelly silt loam	Volcanic	1.16	2	16	82	>150
Hayman	Sphinx, Legault [*sandy-skeletal, mixed, frigid, shallow Typic Ustorthents*], [*sandy-skeletal, paramicaceous, shallow Typic Cryorthents*]	Gravelly sandy loam	Granitic	1.39	3	25	72	20–50
Cannon	Centennial, Ginser [*coarse-loamy, mixed, superactive, thermic Argic Petrocalcids*], [*loamy-skeletal, mixed, superactive, frigid Pachic Haploxerolls*]	Gravelly silt loam	Sedimentary or Granitic	1.15	2	14	84	51–100

Table 3. Precipitation from nearby long-term gauges and overstorey and understorey species for each site

Site	Nearby long-term gauge: Gauge name [distance to site (km)] elevation (m)	Nearby long-term gauge: Mean annual precip. (mm year^{-1}) [No. of years of record]	Overstorey species		Understorey species		
North 25	Pope Ridge Snotel [17] 1080	905 [23]	Grand fir (*Abies grandis*)	Douglas fir (*Pseudotsuga menziesii*)	Oceanspray (*Holodiscus discolour*)	Douglas maple (*Acer glabrum* var. *douglassii*)	Blue elderberry (*Sambucus cerulean*)
Mixing	Idyllwild [7] 1650	646 [51]	Coulter pine (*Pinus coulteri*)	California black oak (*Quercus kelloggii*)	Chaparral whitethorn (*Ceanothus leucodermis*)	Manzanita (*Arctostaphylos* spp.)	
Valley Complex	Saddle Mountain Snotel [22] 2410	915 [28]	Douglas fir (*Pseudotsuga menziesii*)	Ponderosa pine (*Pinus ponderosa*)	Ninebark (*Physocarpus malvaceus*)	Pinegrass (*Calamagrostis rubescens*)	White spirea (*Spiraea betulifolia*)
Fridley	Lick Creek Snotel [14] 2090	755 [28]	Douglas fir (*Pseudotsuga menziesii*)		Snowberry (*Symphoricarpos albus*)	Idaho fescue (*Festuca idahoensis*)	Bluebunch wheatgrass (*Pseudoroegneria spicata*)
Hayman	Manitou Exp. Forest [27] 2390	400 [64]	Ponderosa pine (*Pinus ponderosa*)	Douglas fir (*Pseudotsuga menziesii*)	Common juniper (*Juniperus communis*)	Kinnikinik (*Arctosaphylos uva-ursi*)	Pine dropseed (*Blepharoneuron tricholepis*)
Cannon	Lobdell Lake Snotel [9] 2800	658 [28]	Jeffrey pine (*Pinus jeffreyi*)	Pinyon-juniper (*Pinus edulis*)-(*Juniperus* spp.)	Sagebrush (*Artemisia* spp.)	Antelope bitterbrush (*Purshia tridentata*)	

width of the storage space measured along the same horizontal line (m) (Fig. 1); s was the slope of the LEB measured along the contour (m m^{-1}); and c was the portion of the LEB that had poor ground contact (m m^{-1}), as determined by visual estimate. The variables s and c reduced the storage capacity of the LEB when the log was off-contour or had poor contact with the ground, respectively.

In each year that sediment was produced at a given site, and in summer 2004 at all sites, the LEBs were evaluated to determine sediment-trapping efficiency and quality of performance. Visual estimates of the volume of sediment stored behind the LEBs, t (m^3), were used to calculate the LEB storage ratio, S_{LEB} (%), where:

$$S_{LEB} = \left(\frac{t}{V}\right) 100 \qquad (2)$$

and V (m^3) was the total site LEB storage capacity (Eqn 1). The performance characteristics that compromised the functioning of the LEBs also were evaluated and classified as: (1) evidence of water flow under or around the LEB; (2) settling or installation gap between the LEB and ground surface; (3) evidence of the log rolling or moving away from its original location; or (4) overtopping of the LEB by a sediment plume.

The ground cover was classified in each watershed each year using one of the following three methods. In the North 25 site, ground cover in a 20 × 50-cm plot was visually estimated following Daubenmire (1959), which included a separate visual assessment of vegetative canopy cover for each plot; ground cover and vegetative canopy cover were measured in 20 plots in each watershed. In the Mixing site, 25 randomly located 1-m^2 plots were established and the ground cover was estimated by visual estimate. In all other sites, four to six transects were established per watershed and ground cover was classified using point-quadrat sampling techniques adapted from Chambers and Brown (1983). For all sites, ground cover classes were: bare mineral soil; vegetation including grass, forb, shrub, moss, tree, snag, and tree root (because of the different method at North 25, vegetative canopy cover was not included in total ground cover); litter including root mat and small woody debris ($\leq$2 cm); woody debris including large pieces of wood (>2 cm) and LEBs; and rock, including gravel (>2 mm) and cobbles (>64 mm), except in the North 25 site, where gravel was classified as mineral soil and in the Hayman site where gravel was >10 mm.

Runoff

For each runoff-producing event, the stage, h (mm), was converted to flow rate, Q (m^3 s^{-1}), using the relationship for the control section. For the 300-mm H-flume at the North 25 site, the depth–flow relationship was:

$$Q = 3.41 \times 10^{-7} h^{2.08} \qquad (3)$$

whereas at the Mixing, Valley Complex, and Fridley sites, the depth–flow relationship for the 450-mm H-flumes was:

$$Q = 4.96 \times 10^{-7} h^{2.04} \qquad (4)$$

The depth–flow relationship for the 380-mm V-notch weirs at the Hayman and Cannon sites was:

$$Q = 4.89 \times 10^{-8} h^{2.48} \qquad (5)$$

(USDA 1979). The volume (m^3) of flow through each control structure (flume or weir) was calculated for the duration of each flow event and added to the residual volume in the sediment trap to determine the rain or snowmelt event-driven runoff produced by each watershed. The peak flow rate through the control section was compared with the maximum change in volume in the sediment trap per unit time and the larger of these two values was chosen as the peak flow for each watershed and flow event. All runoff and peak flow values were a combination of water and dissolved, suspended, and bedload sediment. Runoff reported in the current study is storm flow; runoff that was not associated with a rain or snowmelt event occurred in some of the watersheds and this data was not included in our analysis. Runoff data from the LEB-treated watershed at the North 25 site were not consistently recorded and are not presented.

Sediment yield

The sediment accumulated in the sediment traps was periodically removed. For large quantities of sediment, the volume of the accumulated sediment was measured, bulk density samples were taken, and the sediment was removed using mechanical equipment. Smaller quantities of accumulated sediment were manually removed, weighed, and sampled. In the laboratory, the soil water content of the sediment samples was determined and field-measured sediment volumes or weights were converted to dry sediment mass using the bulk density or soil water content.

Data analysis

For all analyses, runoff, peak flow, and sediment yields were divided by the area of each watershed and were expressed as per-unit-area values (mm, m^3 s^{-1} km^{-2}, and Mg ha^{-1}, respectively). Post-fire year was defined to group events that occurred in a single wet season within the same year; thus, the fire year began with the start of the fire and ended on 31 October of the same calendar year. Subsequent post-fire years started 1 November and ended 31 October.

Ground cover was averaged by class for each of the four to six transects (groups of five plots at Mixing) in each watershed. Each transect was then treated as an independent observation of cover for each watershed. Repeated-measures analyses were conducted for each watershed at each site using each transect as the subject and the post-fire year as the period of repetition (Littell *et al.* 1996). Least significant differences were used to compare differences in least-squares means (SAS Institute Inc. 2003).

The runoff, peak flow, and sediment yield data were log-transformed to reduce heteroscedasticity (Helsel and Hirsch 2002). To log-transform data with zero values, 0.003 mm was added to all runoff values, 0.001 m^3 s^{-1} km^{-2} was added to all peak flow values, and 0.003 Mg ha^{-1} was added to all sediment yield values. Repeated-measures analyses were used to test for significant relationships in log-transformed runoff, peak flows, and sediment yields between the treated and control watersheds for each event with complete data. A serial correlation among measurements was included in the repeated-measures models by assuming a spatial power function of the number of days after burning for each event at each site (Littell *et al.* 1996). The rainfall total, I_{10}, and I_{30} were also tested as covariates (Helsel

Table 4. Number of contour-felled log erosion barriers (LEBs), LEB density, mean LEB length, LEB length per unit area, mean LEB diameter, sediment bulk density, and total volumetric and gravimetric site storage capacities for the six sites

Site	No. of LEBs	LEB density (no. ha^{-1})	LEB length (m)	LEB length per unit area (m LEB ha^{-1})	LEB diameter (mm)	Sediment bulk density (Mg m^{-3})	Total unit-area storage capacity (m^3 ha^{-1})	Total unit-area storage capacity (Mg ha^{-1})
North 25[A]	388	46	4.0	184	171	0.97	5.2	5.0
Mixing[A]	157	131	5.5	721	223	1.20	58	70
Valley Complex	333	119	8.8	1047	185	1.41	52	73
Fridley	829	70	8.4	588	213	1.25	38	48
Hayman	340	110	7.7	847	186	1.03	67	69
Cannon[A]	980	90	3.6	324	184	0.99	16	16

[A]No end berms installed above LEBs. End berms increased storage capacity by 16% at the Valley Complex site; the change in capacity was not calculated for the Fridley or Hayman sites.

and Hirsch 2002). In some cases, more than one event occurred between sediment measurements. For these events, the total rainfall and sediment yield and the maximum rainfall intensities were used for the event-based analysis. These statistical models took the form

$$\log_{10}(Y_{ij} + \Delta) = \beta_0 + \beta_1 \log_{10}(X_{ij} + \Delta) + \beta_2 Z_{ij} + \beta_3 T_{ij} + \varepsilon_{ij} \quad (6)$$

where Y_{ij} was the runoff (mm), peak flow ($m^3\ s^{-1}\ km^{-2}$), or sediment yield (Mg ha^{-1}) in the *i*th treated watershed for the *j*th event; Δ was the zero value offset (0.003, 0.001, or 0.003 for runoff, peak flow, and sediment yield, respectively); X_{ij} was the runoff, peak flow, or sediment yield in the *i*th control watershed for the *j*th event; β_0 was the model intercept; β_1 was the modelled slope for the logarithm of X_{ij}; Z_{ij} were the rainfall parameters from the treated watershed (event rainfall in mm, I_{10} in mm h^{-1}, or I_{30} in mm h^{-1}) for the *i*th site and the *j*th event; β_2 was the modelled slope for Z_{ij}; T_{ij} was the number of years after burning for the *i*th site and the *j*th event; β_3 was the modelled slope for T_{ij}; and ε_{ij} was the residual error for the *i*th site and the *j*th event. Because of a lack of independence between rainfall characteristics, only the most significant *Z*, if any, was retained in the model. To evaluate site by site differences, models were also calculated for each site using the same variables as the models developed for all sites together.

To interpret the statistical significance of the runoff, peak flow, and sediment yield results, the modelled relationships between the treated and control watersheds were compared with an ideal pretreatment relationship. As it was impossible to establish a calibration period before treatment, the pretreatment response for each treated watershed was assumed to be equal to the response of its respective control watershed (i.e. a 1 : 1 ratio). If the confidence limits of β_1 (slope in Eqn 6) included 1, there was no difference between the measured relationship and the assumed pretreatment relationship and, therefore, no treatment effect.

Multiple regression analysis with forward selection was used to determine the controlling factors on the LEB storage capacities. The significance level was 0.05 for all tests unless otherwise noted.

Results

Contour-felled logs

Over 3000 LEBs were measured in total immediately after installation at the six sites. The LEB mean length at each site was between 4 and 9 m, and the mean diameter ranged from 171 to 223 mm (Table 4). The LEB density varied from 46 to 131 LEBs ha^{-1} (Table 4). The North 25 site had the lowest LEB density and the second lowest mean LEB length, and this resulted in the lowest total length of LEB per unit area (184 m LEB ha^{-1}) and the lowest unit-area storage capacity (5.0 Mg ha^{-1}). In contrast, the Valley Complex site had the second greatest LEB density and the greatest mean LEB length, yielding the greatest site storage capacity (73 Mg ha^{-1}) (Table 4). As this suggests, as the number and length of LEBs per unit area increased, the potential storage capacity also increased. Indeed, the LEB length per unit area (m LEB ha^{-1}) was the best predictor of the site storage capacity ($n = 6$, $P = 0.01$, $R^2 = 0.82$).

Precipitation

Based on data from the long-term rain gauges, all sites had mean annual precipitation values below the long-term averages for at least half of the study. Of the 26 site-years of precipitation data available during the study period, 19 were below the long-term average for the site. With the exceptions of the Mixing and Hayman sites, these low rainfall amounts resulted in relatively few events that produced runoff or sediment (Table 5). Of the 63 events that produced runoff in at least one of the matched watersheds during the study, 60 were from rainfall and only three were from snowmelt (13 April 2003 and 4 April 2006 at Valley Complex and 13 March 2003 at Fridley). The minimum sediment-producing rainfall was 3.6 mm (North 25) and the minimum sediment-producing I_{10} was 3 mm h^{-1} (Mixing). Of the 60 rain events, 10 were large events with return periods of at least 2 years for the 10-min duration (Table 5). By this definition, only the Hayman site did not experience any large rain events during the study and only the Fridley and Valley Complex sites had large events during the first 2 post-fire years (Table 5).

In addition to the 60 rain events that produced runoff, 1589 storms with durations of at least 5 min occurred in post-fire years 1 through 4 but did not produce runoff. The median I_{10} of the events that did not produce runoff was 3 mm h^{-1}. In

Table 5. Event date, rainfall, 10-min and 30-min maximum intensities (I_{10} and I_{30}), total runoff, runoff to rainfall ratio, peak flow rate, and total sediment yield for the 63 events that produced runoff or sediment in at least one watershed at each site

Rainfall and rainfall intensity values are means of all available gauges in each site. Data for the 10 large storms ($I_{10} \geq$ 2-year return period) are in bold. Return periods for the 10- and 30-min durations that were at least 2 years, are listed as superscripts in the I_{10} and I_{30} columns, respectively. Table symbols include: C, control; T, treated with contour-felled log erosion barriers; n.d., missing data because of equipment malfunction; Σ, sediment combined for multiple events; and SM, snowmelt. Runoff or Peak flow values of <0.1 are shown as '0'

Site	Date [post-fire year]	Rainfall (mm)	I_{10} (mm h^{-1})	I_{30} (mm h^{-1})	Runoff (mm)		Runoff–rainfall ratio (%)		Peak flow rate ($m^3 s^{-1} km^{-2}$)		Sediment yield (Mg ha^{-1})	
					C	T	C	T	C	T	C	T
North 25	15 Jun 99[A] [1]	5.8	16	8	0	Not measured	0	Not measured	0	Not measured	0	0.31
	21 Jul 99[A,B] [1]	3.6	19	12	0		0		0		0	0.74
	6 Aug 99[A] [1]	11.0	31	18	0.3		2.7		0		0.45	0.13
	30 Aug 99[A] [1]	13.3	8	6	1.2		9.0		0.02		0.19	0
	25 Aug 02[C] [4]	**25.1**	**$40^{10–25}$**	**$24^{10–25}$**	**0**		**0**		**0**		**0.17**	**0**
Mixing	25 Jan 00[E] [1]	17.0	9	7	0	0.4	0	2.4	0	0.3	0	0.02
	10 Feb 00[E] [1]	14.0	9	7	0	0.1	0	0.7	0	0.1	0	Σ
	13 Feb 00[E] [1]	16.8	3	2	0	0.2	0	1.2	0	0.1	0	0
	16 Feb 00[E] [1]	15.0	11	6	0	0.1	0	0.7	0	0.2	0	0.12
	23 Feb 00[C] [1]	14.1	8	6	0.1	0.1	0.7	0.7	0	0.1	0	0.01
	18 Apr 00[C] [1]	22.2	11	7	n.d.	0.1	n.d.	0.5	n.d.	0	0.01	0.06
	15 Aug 00[C] [1]	12.3	24	13	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0	0.09
	24 Aug 00[C] [1]	14.2	18	9	n.d.	0.1	n.d.	0.7	n.d.	0.1	0	0.06
	7 Sep 00[C] [1]	14.4	17	8	n.d.	0.1	n.d.	0.7	n.d.	0.1	0.01	0.07
	29 Oct 00[C] [1]	18.5	9	5	n.d.	0.1	n.d.	0.5	n.d.	0.1	0	0.01
	10 Jan 01[C] [2]	13.6	11	6	n.d.	0.1	n.d.	0.7	n.d.	0.1	Σ	Σ
	13 Jan 01[C] [2]	15.6	11	7	n.d.	0.1	n.d.	0.6	n.d.	0	0.01	0.01
	14 Feb 01[C] [2]	12.2	6	4	n.d.	0.1	n.d.	0.8	n.d.	0	Σ	0.01
	6 Mar 01[C] [2]	12.7	8	6	0.6	0	4.7	0	0	0	0	0
	6 Aug 01[C] [2]	15.6	38	18	0.3	n.d.	1.9	n.d.	0.1	n.d.	1.34	0.06
	24 Nov 01[C] [3]	22.2	21	13	0.3	n.d.	1.4	n.d.	0.4	n.d.	0	0
	15 Mar 03[C] [4]	72.3	16	11	0.6	n.d.	0.8	n.d.	0.1	n.d.	0	0
	25 Feb 04[C] [5]	36.2	11	7	0.1	n.d.	0.3	n.d.	0	n.d.	0	0
	2 Mar 04[C] [5]	18.0	11	7	0	n.d.	0	n.d.	0	n.d.	0	0
	9 Sep 04[C] [5]	**65.5**	**$75^{5–10}$**	**$63^{25–50}$**	**1.0**	**1.6**	**1.5**	**2.4**	**1.1**	**0.9**	**Σ**	**Σ**
	18 Oct 04[C] [5]	101.7	21	16	0.6	0.5	0.6	0.5	0.1	0	0.44	0.05
	27 Oct 04[C] [5]	42.5	12	8	0.1	0.3	0.2	0.7	0	0	0	0
	21 Nov 04[E] [6]	7.1	8	5	0.1	0.1	1.4	1.4	0	0	0	0
	28 Dec 04[C] [6]	100.1	17	11	0.7	0.8	0.7	0.8	0.1	0	0.73	0
Valley Complex	27 Apr 01 [1]	7.4	30	12	0	0	0	0	0	0	0.08	0
	20 Jul 01 [1]	**9.1**	**42^{5}**	**18^{2}**	**0**	**0.1**	**0**	**1.1**	**0.2**	**0.1**	**Σ**	**Σ**
	21 Jul 01 [1]	**9.9**	**32^{2}**	**18^{2}**	**0**	**0.1**	**0**	**1.0**	**0.1**	**0.1**	**0.56**	**0.15**
	29 Jul 01[C] [1]	28.8	6	5	0	0	0	0	0	0	0	0

(*Continued*)

Table 5. (Continued)

Site	Date [post-fire year]	Rainfall (mm)	I_{10} (mm h^{-1})	I_{30} (mm h^{-1})	Runoff (mm)		Runoff–rainfall ratio (%)		Peak flow rate ($m^3 s^{-1} km^{-2}$)		Sediment yield (Mg ha^{-1})	
					C	T	C	T	C	T	C	T
	14 Apr 02[C] [2]	13.5	13	7	1.5	0	11.1	0	0	0	0.11	0
	19 Jul 02 [2]	**23.6**	**59^{25}**	**43^{50}**	**0.3**	**0.1**	**1.3**	**0.4**	**0.2**	**0.2**	**0.38**	**0.33**
	21 Aug 02 [2]	**12.7**	**32^{2}**	**14**	**0.2**	**0.2**	**1.6**	**1.6**	**0.3**	**0.2**	**0.44**	**0.15**
	13 Apr 03[C,F] [3]	1.1	5	2	5.7	0	SM[F]	SM[F]	0	0	0.09	0
	4 Apr 06[F] [6]	18.9	12	11	2.5	0.1	SM[F]	SM[F]	0	0	0.12	0
Fridley	18 Jun 02[C] [1]	18.5	23	11	0	0.1	0	0.5	0	0.1	0	0.12
	6 Jul 02 [1]	10.6	34	17	0	0.1	0	0.9	0	0.1	0	0.18
	20 Jul 02 [1]	**14.9**	**55^{5}**	**$28^{2–5}$**	**0.3**	**0.2**	**2.0**	**1.3**	**0.5**	**0.4**	**Σ**	**Σ**
	25 Jul 02 [1]	**14.2**	**$47^{2–5}$**	**17**	**n.d.**	**n.d.**	**n.d.**	**n.d.**	**0.2**	**n.d.**	**Σ**	**Σ**
	27 Jul 02 [1]	**20.6**	**$45^{2–5}$**	**22^{2}**	**n.d.**	**n.d.**	**n.d.**	**n.d.**	**0**	**n.d.**	**6.70**	**5.81**
	13 Mar 03[F] [2]	4.8	3	2	4.7	0.3	SM[F]	SM[F]	0.3	0.4	0.29	0.16
	18 Aug 05 [4]	7.1	24	12	0.1	0	1.4	0	n.d.	0	0.01	0.01
	23 Sep 05 [4]	27.2	18	11	0.1	0	0.4	0	n.d.	0	0.01	0
Hayman[D]	1 Oct 02 [fire year]	30.5	9	7	2.1	0	6.9	0	2.4	0	0.74	0.07
	18 Jul 03 [1]	4.6	13	5	0	0	0	0	0	0	0.01	0
	29 Jul 03[E] [1]	4.3	23	8	0	0	0	0	0	0	0	0.03
	9 Aug 03[E] [1]	18.0	52	28	8.6	5.3	47.8	29.4	5.0	5.0	19.80	9.40
	30 Aug 03 [1]	29.0	23	16	5.4	1.7	18.6	5.9	3.7	2.6	4.58	1.99
	18 Jun 04[E] [2]	4.1	15	6	0	0	0	0	0	0	Σ	0
	22 Jun 04 [2]	11.6	9	5	0	0	0	0	0	0	Σ	0
	27 Jun 04 [2]	10.4	17	10	0.8	0.5	7.7	4.8	2.6	2.2	3.06	0.78
	22 Jul 04 [2]	9.0	10	4	0	0	0	0	0	0	0.02	0
	5 Aug 04 [2]	6.9	16	7	0.4	0.1	5.8	1.4	2.5	0.2	Σ	Σ
	6 Aug 04 [2]	8.0	13	7	0.1	0	1.3	0	0.4	0	1.33	0.04
	19 Aug 04 [2]	11.7	27	11	0.8	0.8	6.8	6.8	2.4	1.9	2.29	0.45
	27 Aug 04 [2]	9.0	21	11	0.2	0.1	2.2	1.1	0.4	0.1	0.41	0.09
	27 Sep 04 [2]	11.7	12	9	0	0	0	0	0	0	0.03	0
Cannon	6 Nov 02[C] [1]	99.8	29	15	0.1	0.1	0.1	0.1	0	0	0.13	0.12
	14 Apr 03 [1]	19.5	10	67	0	0	0	0	0	0	0.01	0
	18 Jul 06 [4][G]	**30.0**	**134^{100}**	**58^{100}**	**0.6**	**0.9**	**2.0**	**3.2**	**1.0**	**1.6**	**9.7**	**15.2**

[A] Only three gauges were available for the two watersheds for this event.
[B] The rain data had high ranges across the available gauges: rainfall 0.8–6.9 mm; I_{10} 3–40 mm h^{-1}; and I_{30} 2–14 mm h^{-1}.
[C] Only two gauges were available for the two watersheds for this event.
[D] Only two gauges were available for the two watersheds for this site.
[E] Only one gauge was available for the two watersheds for this event.
[F] The runoff and sediment produced by this event were caused by snowmelt.
[G] Data from this storm were incomplete, and these are measured values from the limited dataset; actual runoff, peak flow, and sediment yields were probably much greater.

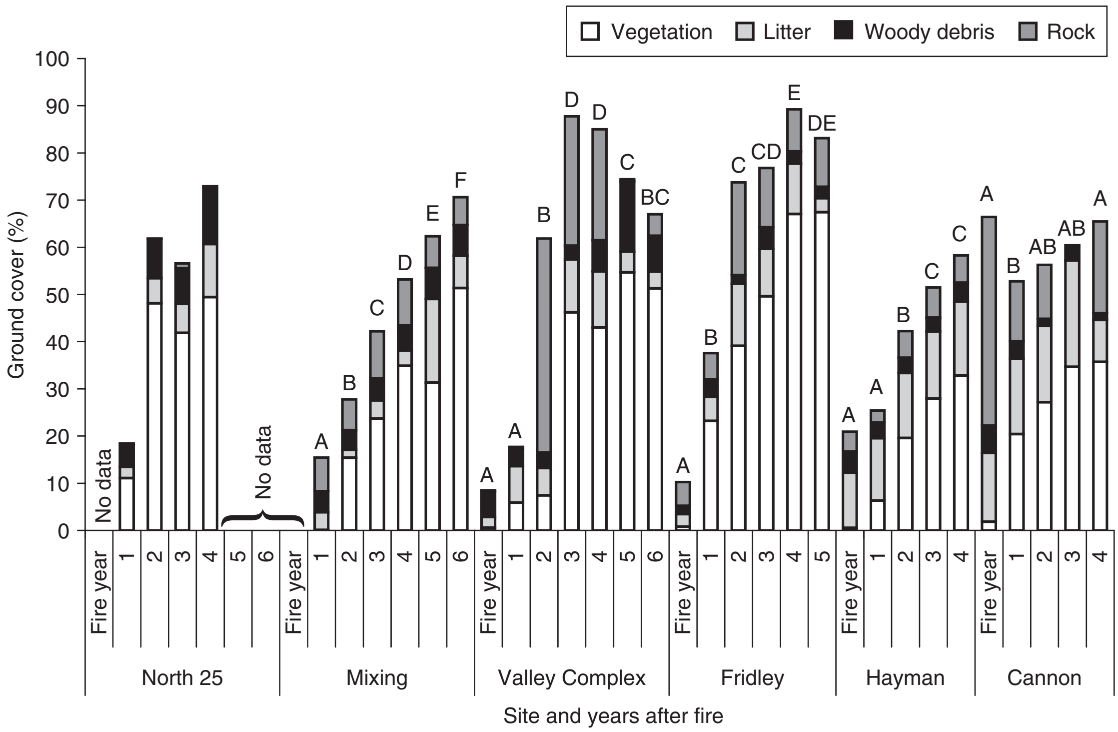

Fig. 4. Mean ground cover for each year after burning at each site. Different letters within a site indicate significant differences from the least significant differences test of least-squares means ($\alpha = 0.05$). Ground cover data were not collected in the North 25 watersheds in the fire year and in post-fire years 5 and 6 or in the Mixing watersheds in the fire year. Vegetative cover data for North 25 site were measured using a different method than at the other sites and are not included in the analysis.

the first post-fire year, the maximum I_{10} for non-runoff producing events ranged from $9\,mm\,h^{-1}$ (Mixing) to $34\,mm\,h^{-1}$ (Valley Complex), whereas in the second year the range of I_{10}s for non-runoff-producing events was from $11\,mm\,h^{-1}$ (Mixing) to $41\,mm\,h^{-1}$ (Fridley). These values continued to increase in post-fire years 3 and 4, and the range of maximum I_{10}s that did not produce runoff in post-fire year 4 was $15\,mm\,h^{-1}$ (North 25 and Cannon) to $46\,mm\,h^{-1}$ (Hayman). Although the events that did produce runoff generally had I_{10}s of at least $7\,mm\,h^{-1}$ (Table 5), events with greater intensity occurred without producing measurable runoff at the watershed outlet. The post-fire years 3 and 4 had fewer runoff events except when higher-intensity rain occurred (Table 5).

Ground cover

There was no difference in ground cover between the control and treated watersheds in any site or year with the exception of the Cannon site in the fire year and first post-fire year (data not shown). The vegetative component of cover increased significantly in each site over the course of the study, thus significantly increasing the ground cover at all sites except in North 25, where vegetation was measured separately from ground cover, and in Cannon, where high initial measures of rock cover were later concealed by vegetation (Fig. 4). The lack of a difference in ground cover between the control and treated watersheds in almost all sites and years suggests that the LEB treatment had little or no effect on the natural post-fire ground cover or the vegetative recovery processes.

Runoff and peak flows

There was a large range in values for runoff and peak flow among the sites and between the treated and untreated watersheds within sites. Across all sites, the maximum runoff was 8.6 mm (48% of the rainfall) following 18 mm of rainfall ($I_{10} = 52\,mm\,h^{-1}$) on 9 August 2003 at the Hayman site (Table 5). The maximum measured runoff values at the other sites were 1.2 mm on 30 August 1999 at North 25 (9% of the event rainfall), 1.6 mm on 9 September 2004 at Mixing (2% of event rainfall), 5.7 mm on 13 April 2003 at Valley Complex (from snowmelt), 4.7 mm on 13 March 2003 at Fridley (from snowmelt), and 0.9 mm on 18 July 2006 at Cannon (3% of event rainfall). The mean peak flow was $0.5\,m^3\,s^{-1}\,km^{-2}$ in the control watersheds ($n = 54$) and only $0.3\,m^3\,s^{-1}\,km^{-2}$ in the treated watersheds ($n = 52$). The overall maximum peak flow ($5.0\,m^3\,s^{-1}\,km^{-2}$) occurred at the Hayman site during the same 9 August 2003 rain event, and all other site maxima ranged between 0.02 and $1.6\,m^3\,s^{-1}\,km^{-2}$ (Table 5).

Modelling the runoff as in Eqn 6, across all events and all sites, the modelled slope between the log-transformed runoff on the treated watersheds and the log-transformed runoff on the control watersheds was 0.35, which means that, on average, the log-transformed runoff on the treated watershed was 35% of the log-transformed runoff on the control watershed (Table 6). Also, the log-transformed peak flow rate in the treated watersheds was 65% of the log-transformed peak flow rate in the control watersheds (Table 6). Both of these relationships were significant. Also, when the storms were classified as large or

Table 6. Statistical model coefficient estimates with 95% lower and upper confidence limits (LCL and UCL), for linear models of log-transformed runoff, peak flow, and sediment yield in the form of Eqn 6

Pretreatment slopes (β_1) for runoff, peak flow, and sediment yield were assumed to be 1; thus if the confidence interval did not include 1, the contour-felled log erosion barriers had a significant effect on the response variable. The intercept (β_0) and the coefficients for rainfall or I_{10} (β_2) and years after burning (β_3) were significant if the confidence interval did not contain 0. Statistically significant effects are shown in bold type. Coefficients for the Cannon site and for some coefficients for the North 25 and Fridley sites were not estimable because of the small number of events at those sites; the coefficients for the Cannon site are not shown. Intercept is abbreviated to 'Int.'

Site	Estimate	Runoff			Peak flow		Sediment yield			
		Int. (β_0)	Runoff slope (β_1)	Rainfall slope (β_2)	Int. (β_0)	Peak flow slope (β_1)	Int. (β_0)	Sed. yield slope (β_1)	I_{10} slope (β_2)	Years after slope (β_3)
North 25	Coefficient	Runoff not measured in treated watershed					Not estimable	−0.36	0.06	−0.76
	(LCL, UCL)							(−7.5, 6.8)	(−0.6, 0.7)	(−4.5, 3.0)
Mixing	Coefficient	**−2.2**	**−0.39**	**0.02**	−1.4	**0.05**	**−1.3**	**0.10**	**0.02**	**−0.24**
	(LCL, UCL)	**(−3.5, −1.0)**	**(−0.9, 0.2)**	**(0.01, 0.04)**	(−2.8, 0.12)	**(−0.6, 0.7)**	**(−2.1, −0.5)**	**(−0.2, 0.4)**	**(0.003, 0.03)**	**(−0.3, −0.2)**
Valley Complex[A]	Coefficient	**−2.0**	**−0.03**	0.02	**−1.1**	0.7	−3.2	0.04	0.05	0.12
	(LCL, UCL)	**(−3.5, −0.5)**	**(−0.8, 0.7)**	(−0.05, 0.1)	**(−1.9, −0.2)**	(0.3, 1.1)	(−11.9, 5.5)	(−4.8, 4.9)	(−0.1, 0.2)	(−0.8, 1.1)
Fridley	Coefficient	Not estimable	0.17	−0.004	−0.31	**0.25**	Not estimable			
	(LCL, UCL)		(−9.2, 9.6)	(−1.1, 1.1)	(−0.8, 0.2)	**(−0.03, 0.5)**				
Hayman	Coefficient	0.05	1.0	−0.04	**−0.78**	0.87	−0.93	0.74	0.004	0.13
	(LCL, UCL)	(−1.4, 1.7)	(0.5, 1.5)	(−0.1, 0.04)	**(−1.4, −0.2)**	(0.5, 1.2)	(−3.2, 1.3)	(0.2, 1.3)	(−0.05, 0.04)	(−1.7, 1.9)
All sites:	Coefficient	**−1.2**	**0.35**	**0.01**	**−0.47**	**0.65**	**−0.88**	**0.34**	**0.02**	**−0.27**
all storms	(LCL, UCL)	**(−1.7, −0.7)**	**(0.09, 0.6)**	**(0.001, 0.02)**	**(−1.2, −0.3)**	**(0.4, 0.9)**	**(−1.5, −0.3)**	**(0.1, 0.6)**	**(0.008, 0.03)**	**(−0.4, −0.2)**
All sites:	Coefficient	**−1.5**	**0.24**	0.01	−0.77	**0.53**	**−1.2**	**0.30**	**0.025**	**−0.22**
small storms	(LCL, UCL)	**(−2.3, −0.6)**	**(−0.07, 0.5)**	(−0.002, 0.03)	(−1.8, 0.3)	**(0.2, 0.9)**	**(−1.9, −0.5)**	**(0.09, 0.5)**	**(0.007, 0.04)**	**(−0.3, −0.1)**
All sites:	Coefficient	0.17	1.0	−0.002	−0.05	1.0	−0.62	0.34	0.02	−0.54
large storms	(LCL, UCL)	(−1.2, 1.5)	(0.3, 1.7)	(−0.04, 0.03)	(−0.4, 0.3)	(0.8, 1.2)	(−4.2, 3.0)	(−1.0, 1.7)	(−0.03, 0.07)	(−1.5, 0.4)

[A]Example interpretation for the runoff model at the Valley Complex site: the intercept (β_0) was significant since the confidence interval did not include 0; the runoff slope (β_1) was significant since the confidence interval did not include 1; and the rainfall slope (β_2) was not significant since the confidence interval did include 0.

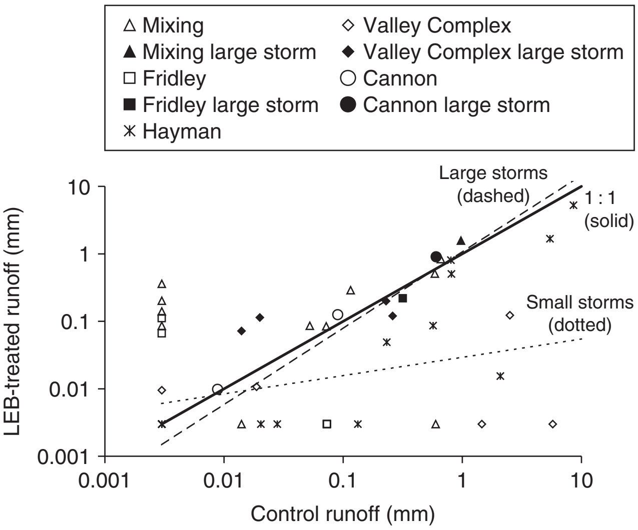

Fig. 5. Runoff rates from the contour-felled log erosion barrier treated watersheds *v.* runoff rates from the control watershed for each event that produced runoff in at least one watershed at each site. No runoff data are available from the North 25 treated watershed. The assumed pretreatment relationship is indicated by the 1 : 1 (solid) line. Large storms were defined as having at least a 2-year return interval for the 10-min duration.

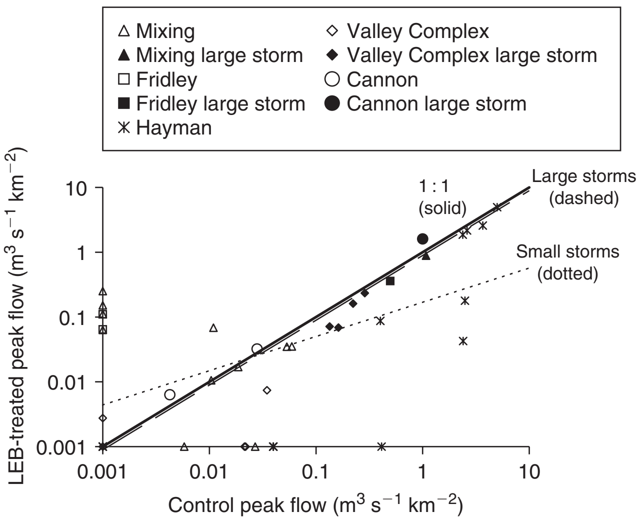

Fig. 6. Peak flow rates from the contour-felled log erosion barrier treated watersheds *v.* peak flow rates from the control watershed for each event that produced runoff in at least one watershed at each site. No peak flow data are available from the North 25 treated watershed. The assumed pretreatment relationship is indicated by the 1 : 1 (solid) line. Large storms were defined as having at least a 2-year return interval for the 10-min duration.

small and the runoff and peak flows were then modelled as in Eqn 6, the confidence intervals for the slopes (β_1) for the small events did not include 1, the assumed pretreatment relationship, whereas the confidence intervals for the slopes for the large events did include 1 (Table 6; Figs 5 and 6). On a site-by-site basis, the slopes of the log-transformed treated *v.* control runoff relationships (β_1) were only significantly different from 1 at the Mixing and Valley Complex sites (Table 6).

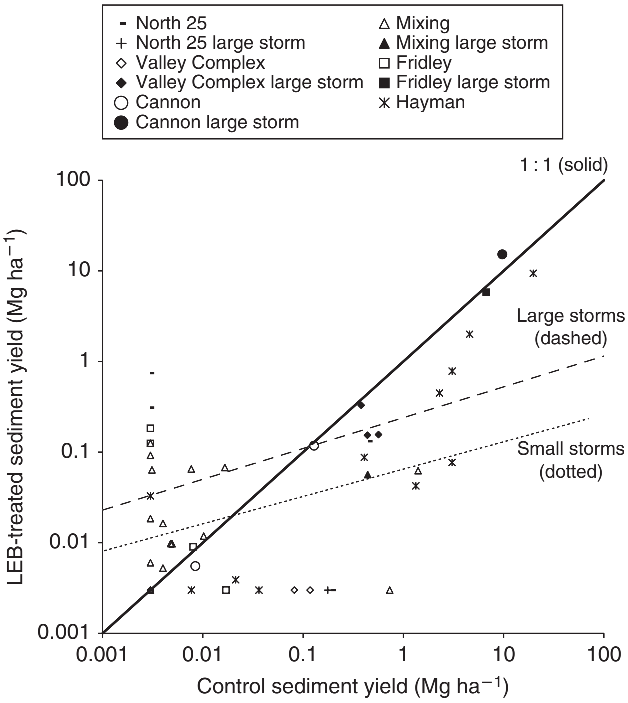

Fig. 7. Sediment yields from the contour-felled log erosion barrier treated watersheds *v.* sediment yields from the control watersheds for each event that produced sediment in at least one watershed at each site. The assumed pretreatment relationship is indicated by the 1 : 1 (solid) line. Large storms were defined as having at least a 2-year return interval for the 10-min duration.

Similarly, the slopes of the log-transformed treated *v.* control peak flow relationships were only significant at the Mixing and Fridley sites (Table 6). The total rainfall was a significant covariate for the log-transformed runoff, as the runoff increased with increasing storm rainfall (Table 6). None of the rainfall characteristics were significant covariates for the log-transformed peak flows. Also, the time since burning did not significantly affect the log-transformed runoff or peak flows.

Although the LEB treatment did not produce a significant effect on runoff and peak flow at each site, consistent trends were observed within sites. The Valley Complex, Fridley, and Hayman sites generally had more runoff and greater peak flows in the control watershed than in the treated watershed (Table 5). In contrast, the Mixing and Cannon sites typically had greater runoff in the treated watershed than in the control watershed (Table 5). In the Mixing site, peak flows were greater in the treated watershed than in the control watershed for the first five events, whereas in the Cannon site, peak flows were greater in the treated watershed for the one event with a measurable peak flow (Table 5).

Sediment yields

As with the runoff and peak flow data, there was a large range in measured event and annual sediment yields within and among sites. The control watershed at the Hayman site produced 19.8 Mg ha^{-1} of sediment during the 9 August 2003 event, and this was the greatest sediment yield from any event at any watershed (Table 5). The largest event sediment yields for the other sites were 0.7 Mg ha^{-1} in North 25, 1.3 Mg ha^{-1} in Mixing, 0.6 Mg ha^{-1} in Valley Complex (the result of two events), 6.7 Mg ha^{-1} in Fridley (the result of three events), and 15.2 Mg ha^{-1} in Cannon (Table 5). Except for the North 25 and Cannon sites, these maxima occurred in the control watersheds.

When the event-based sediment yields from all sites were analysed as in Eqn 6, the relationship between the log-transformed LEB-treated and control sediment yields was significantly different from 1, indicating a significant treatment effect (Fig. 7). The modelled slope for this relationship was 0.34 (Table 6), which means that, on average, the log-transformed sediment yield in the LEB-treated watershed was 34% of the log-transformed sediment yield in the control watershed. As with the runoff and peak flows, there was a significant treatment effect on sediment yield for the small rain events but not for the large events (Table 6; Fig. 7). On a site-by-site basis, only Mixing had significant treatment effects on sediment yields (Table 6).

The I_{10} and years after burning were significant covariates in the log-transformed sediment yield model based on Eqn 6 (Table 6; Fig. 8). The log-transformed watershed sediment yields increased significantly with greater I_{10} (Fig. 8) and decreased significantly with more years since burning (Table 6).

As with the runoff and peak flow results, the event sediment yield data reflected trends within sites. The North 25, Valley Complex, and Hayman sites generally had lower sediment yields in the LEB-treated watershed than in the control watershed (Table 5). Conversely, the treated watershed produced greater sediment yields than the controls for 13 of the 17 events at the Mixing site, and 9 of these were in the first post-fire year.

On an annual basis, the first-year total sediment yields in the control watersheds ranged from 0.14 Mg ha^{-1} year^{-1} (Cannon) to 24.4 Mg ha^{-1} year^{-1} (Hayman) (Table 7). Similarly, the first-year sediment yields in the treated watersheds ranged from 0.12 Mg ha^{-1} year^{-1} (Cannon) to 11.4 Mg ha^{-1} year^{-1} (Hayman). The Mixing, Valley Complex, Fridley, and Hayman sites produced sediment in the 2nd year after burning. These yields ranged from 0.01 Mg ha^{-1} year^{-1} (Cannon) to 7.1 Mg ha^{-1} year^{-1} (Hayman) in the untreated watersheds, and from 0 Mg ha^{-1} year^{-1} (Cannon) to 1.4 Mg ha^{-1} year^{-1}

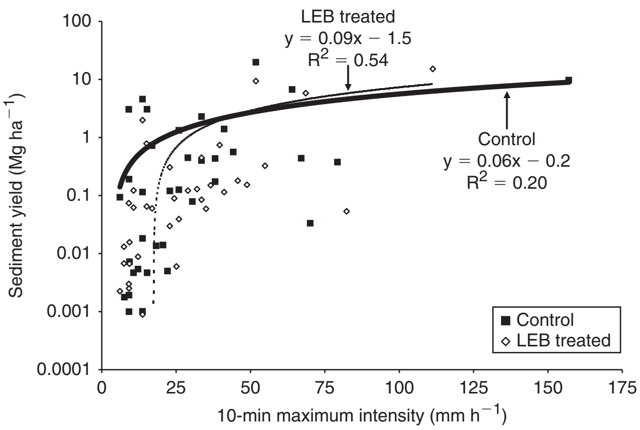

Fig. 8. Sediment yield from the contour-felled log erosion barrier treated and control watersheds *v.* 10-min maximum intensity (I_{10}) for all sediment-producing events.

Table 7. Number of precipitation events that produced runoff out of the total number of rain events and annual sediment yields for the first four years at each site

Durations for rain events were at least 5 min. Sediment yields are in Mg ha^{-1}. C, control watershed; T, treated with log erosion barriers (LEB). Total, the total number of rain events that produced runoff out of the total rain events for all sites for each year; Mean, the mean sediment yield across all sites for each year

Site	1st post-fire year			2nd post-fire year			3rd post-fire year			4th post-fire year		
	No. of runoff-producing rain events/total rain events	Sediment yields (Mg ha^{-1} year^{-1})		No. of runoff-producing rain events/total rain events	Sediment yields (Mg ha^{-1} year^{-1})		No. of runoff-producing rain events/total rain events	Sediment yields (Mg ha^{-1} year^{-1})		No. of runoff-producing rain events/total rain events	Sediment yields (Mg ha^{-1} year^{-1})	
		C	T		C	T		C	T		C	T
North 25	4/79	0.64	1.20	0/60	0	0	0/79	0	0	1/52	0.17	0
Mixing	13/48	0.02	0.44	5/55	1.35	0.08	1/38	0	0	1/54	0	0
Valley Complex	4/100	0.64	0.15	3/86	0.93	0.48	1/47	0.09	0	0/51	0.12	0
Fridley	5/98	6.70	6.11	1/120	0.29	0.16	0/109	0	0	2/121	0.02	0.01
Hayman	4/38	24.4	11.4	9/68	7.14	1.36	0/50	0	0	0/88	0	0
Cannon	2/42	0.14	0.12	0/61	0.01	0	0/37	0	0	1/66	9.7	15.2
Total	32/404			18/450			2/360			5/432		
Mean		5.4	3.2		1.6	0.35		0.02	0		1.7	2.5

(Hayman) in the treated watersheds (Table 7). All sites except Hayman had measurable sediment yields more than 2 years after the fire (Table 5). These higher-year sediment yields were greater in the control watersheds than in the treated watersheds except at the Cannon site in post-fire year 4, where one very large storm produced more sediment in the treated watershed (Table 5).

Contour-felled log erosion barrier storage ratios and performance

As might be expected from the significant treatment effects, the LEBs stored some sediment in the watersheds at each site. Based on the 2004 sediment storage estimates, the LEBs stored between 20 m^3 (Valley Complex) and 140 m^3 (Fridley). The LEB storage ratio (S_{LEB}, Eqn 2) values ranged from 14% (Valley Complex) to 78% (North 25) (Table 8).

Table 8. Contour-felled log erosion barrier (LEB) sediment storage ratio (S_{LEB}) (Eqn 2) by post-fire year and site

'n.e.' indicates the volume of sediment stored behind the LEBs was not estimated

Site	Sediment storage ratio (S_{LEB}) Post-fire year					
	1	2	3	4	5	6
North 25	63	63[A]	63[A]	n.e.	99	78
Mixing	n.e.	13	10	21	71	71[A]
Valley Complex	6	2	36	14	14[A]	n.e.
Fridley	37	47	33	n.e.	n.e.	
Hayman	17	43	43[A]	43[A]		
Cannon	0.7	47	47[A]	61		

[A]No sediment was produced from the treated watershed after the previous sediment estimate.

In the 2004 LEB survey, 25% of all logs sampled had no performance deficiency (Fig. 9). The most commonly observed LEB defect was a log slope of more than 5% off-contour, which occurred in 38% of all sampled LEBs across all sites. The other defect rates were: a gap between log sections and the ground surface due to poor installation or settling over time (33% of sampled LEBs); evidence of water flowing under or around the ends of the LEBs, which occurred on 23% of the LEBs sampled; a sediment plume overtopping the LEB without completely filling the storage volume (17% of LEBs sampled); and movement or rolling of the LEB (8% of LEBs sampled) (Fig. 9). The frequency of these faults varied by site (Fig. 9).

Two types of LEB defects were correlated with LEB dimensions. The proportion of LEBs that had moved decreased with increasing mean LEB length ($R^2 = 0.83$, $n = 6$). This suggests that longer LEBs were less likely to move once they were anchored in place. The lowest defect rates for LEB movement were at Valley Complex (2%), Fridley (5%), and Hayman (5%) (Fig. 9). These sites also had the greatest mean LEB lengths (8.8 m, 8.4 m, and 7.7 m, respectively). Also, the proportion of LEBs that overtopped decreased with increasing LEB density (number of LEBs ha^{-1}) ($R^2 = 0.72$, $n = 6$).

Discussion

The runoff, peak flow, and sediment yield results show that LEBs can provide a significant treatment effect, reducing the log-transformed responses by as much as 65% as compared with the controls (Table 6). However, these results may be somewhat misleading because 56 of the 66 responses resulted from small rain storms or snowmelt. Because of the data bias towards small storms, it is impossible to discuss the results without addressing the relative magnitude of the storms that occurred, as measured by the return period.

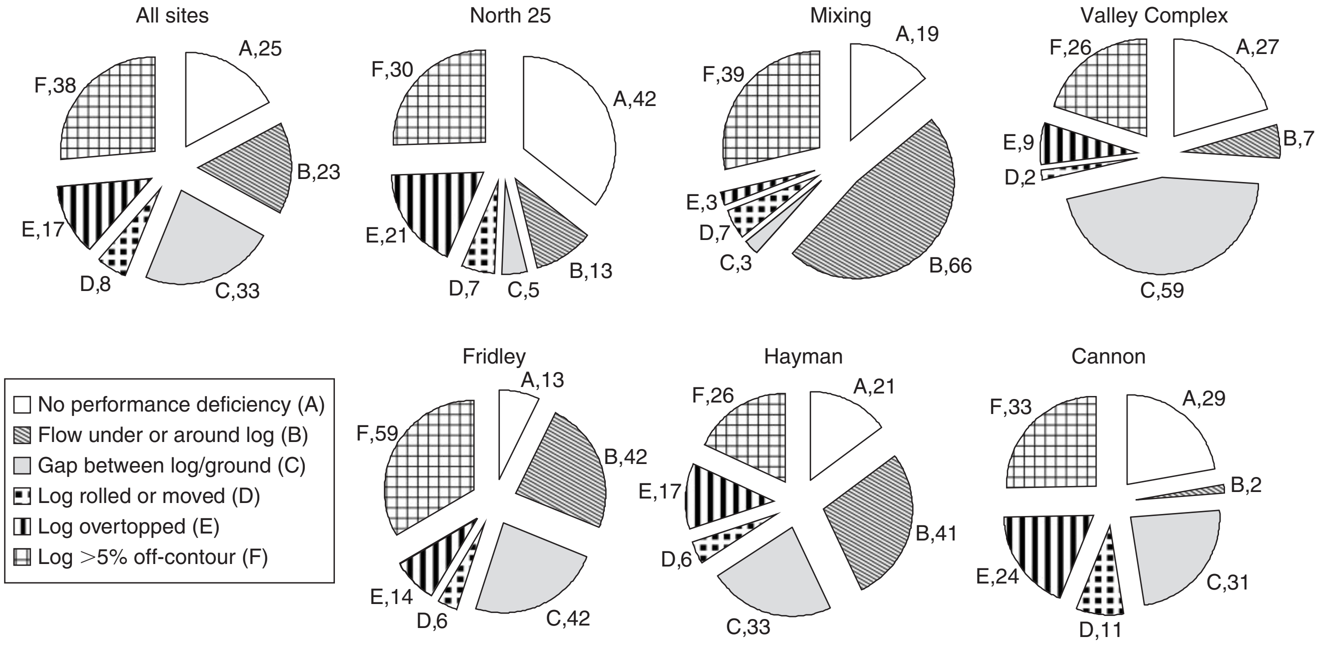

Fig. 9. Proportion of sampled logs by defect type for all sites and for individual sites. Proportions may not total 100%, as multiple defect types may have occurred on individual logs. The survey was conducted in summer 2004.

The Mixing site was the only site to produce significant treatment effects on sediment yield on an individual basis (Table 6). The Mixing site had the second highest storage capacity (Table 4) and the maximum sediment stored behind the LEBs ($41\,m^3\,ha^{-1}$). This probably was the cause for the significant reduction in sediment yields at this site. However, the Hayman site, which had the greatest storage capacity (Table 4) and stored $29\,m^3\,ha^{-1}$ of sediment, showed no significant treatment effects, and this was likely a result of the wide range in responses measured over the 4-year period (Table 5). For the other sites, the lack of a significant treatment effect was a result of the relatively small amount of sediment stored behind the logs (3.0 to $13\,m^3\,ha^{-1}$).

The control watershed in the Hayman site had greater measured runoff and sediment yield values than all other sites in the study. These study-wide maxima resulted from a first post-fire year storm with an I_{10} of $52\,mm\,h^{-1}$ (Table 5), which was less than the 2-year, 10-min storm ($56\,mm\,h^{-1}$) calculated for the Hayman site. Although the Hayman LEB-treated watershed had 39% less runoff and 47% less sediment yield than the control for this storm, the sediment yield from the treated watershed was still $9.4\,Mg\,ha^{-1}$, the fourth largest measured event sediment yield during the 31 study-site years. This magnitude of erosion likely would be considered unacceptable, especially after treatment, by most land managers. Despite the small storm classification and the limited effectiveness of the LEB treatment, the observed large response was a result of the high rainfall intensity of this event.

There were over 1500 rain events in the first 4 post-fire years that did not produce runoff in the control watersheds, and 382 of those had I_{10}s greater than $7\,mm\,h^{-1}$, a rain intensity that often produced runoff (Table 5). Although rainfall intensity was a key factor controlling post-fire sediment yields (Table 6) (Moody and Martin 2001*a*), these data suggest that site conditions, which can vary over a single season, also influence the extent and magnitude of those responses. Although not considered in this analysis, it was likely that general site conditions, such as soil moisture, degree of soil water repellency, and the degree of post-fire recovery, influenced the watershed responses to rainfall events.

When we compared the runoff, peak flows, and sediment yields between the control and treated watersheds for large and small events, only the small events produced a significantly smaller slope than the assumed equivalence. These results suggest that LEBs were an effective treatment for reducing runoff and peak flow for small events, but not for large events (Table 6; Figs 5 and 6). The sediment yields also showed a treatment effect for small storms but not for large storms (Table 6). Although the slopes in the sediment yield models for small and large events are nearly equal (Fig. 7), the confidence interval of the slope for the large events is much greater and includes 1 (Table 6). The difference in the regression lines between the treated and the control watersheds for the sediment yield response to I_{10} also suggests a treatment effect for small rain events and no treatment effect for large rain events (Fig. 8). This result is similar to results in two previous studies where LEBs were evaluated at smaller scales. One study found LEBs were ineffective in large storms but could be effective for small events given sufficient sediment-storage capacity (Wagenbrenner *et al*. 2006). Another study found LEBs were effective at reducing runoff from simulated low-intensity rainfall and inflow but did not reduce erosion from either simulated low-intensity rainfall and inflow or natural rainfall (Robichaud *et al*. 2008).

Rills were often observed around the ends of LEBs that were installed off-contour and underneath LEBs that had gaps between the LEB and the soil surface. In these cases, the LEBs acted as runoff collectors, and the concentrated flow leaving the LEBs probably had greater flow velocity and sediment-carrying capacity than the less concentrated flow from above the LEB. This likely resulted in greater local erosion rates than if the LEBs had not been installed. About one-quarter of all the LEBs inspected in 2004 showed evidence of flow beneath or around the ends; yet, there was sufficient storage capacity in both the defective LEBs (often able to store some runoff and sediment), and the properly installed LEBs downslope of the defective LEBs to produce a net reduction in runoff and sediment yields at the small-watershed scale.

With the exception of one site (Valley Complex), the eroded sediment trapped by LEBs generally filled between 33 and 78% of the total LEB sediment storage capacity (Table 8). The S_{LEB}s (Eqn 2) estimated at the six sites in the present study were very similar to the sediment-trapping efficiency reported in an earlier plot-scale LEB study (Robichaud *et al*. 2008). Based on observations, LEBs frequently intercepted concentrated flow with entrained sediment and the sediment was deposited in a small section of the LEB, leaving much of the total sediment storage capacity unused. These observations, combined with the LEB performance survey results (Fig. 9), indicate that LEB sediment-trapping efficiency could be improved by (1) adding soil berms to the ends of the LEBs; (2) increasing the LEB length per unit area; and (3) increasing quality control during LEB installation to ensure that LEBs are placed on contour, securely anchored to the ground, and gaps between the LEB and the ground are sealed. However, these improvements would also increase installation time and cost.

At the Mixing site, the sediment yields in the first post-fire year were greater in the treated watershed than in the control watershed; however, in post-fire years 2 and 3, the sediment yields generally were greater in the control than in the LEB-treated watershed. Also, in both the North 25 site and the Fridley site, the first two sediment-producing rain events produced sediment in the treated watersheds but not in the untreated control watersheds (Table 5). Although differences in rainfall intensity between the treated and control watersheds were observed, these results suggest that LEB installation may cause enough soil disturbance to produce an increase in sediment yields, especially in the first few storms after installation. This response to LEB installation was not observed at the Hayman and Valley Complex sites where, with the exception of one sediment-producing event (Hayman, 29 July 2003), the greater sediment yields were always in the untreated watersheds (Table 5).

Few studies have measured post-fire runoff or peak flows, and even fewer have measured these effects at the small-watershed scale. However, using runoff efficiency (the ratio of runoff to rainfall), results from the current study can be compared with unburned conditions and with recent post-fire studies. Springer and Hawkins (2005) reported a range in runoff efficiencies of 0.08 to 2.0% from unburned forests throughout the western USA and from 0.03 to 19% in a burned 210-ha watershed in northern New Mexico. Kunze and Stednick (2006) reported runoff efficiencies of up to 17%, whereas the majority of the events had runoff of less than 2% of rainfall. In comparison, the greatest runoff efficiency in the present study was 48%, which occurred on the Hayman control watershed after a storm with an I_{10} of 52 mm h^{-1}, whereas the maximum efficiency was less than 12% at each of the other sites (Table 5). In the current study, the majority of runoff efficiencies were 2% or less and this range was similar to the values reported by both Springer and Hawkins (2005) and Kunze and Stednick (2006). The Hayman site, with an average runoff efficiency of 8%, was the exception within the present study and differed substantially from the results of Kunze and Stednick (2006) despite its similar location in the Colorado Front Range.

Generally, larger post-fire runoff and peak flow rates have been estimated from smaller areas (Gartner *et al*. 2004; Neary *et al*. 2005), but our results do not reflect this trend. The largest peak flow in the present study (5.0 $m^3 s^{-1} km^{-2}$) occurred at the Hayman site, and this value was similar to the maximum peak flow rate of 3.9 $m^3 s^{-1} km^{-2}$ reported by Kunze and Stednick (2006). Moody and Martin (2001*a*) reported a peak flow rate of $\sim$19 $m^3 s^{-1} km^{-2}$ from the burned Spring Creek watershed, and this value was approximately four times larger than the maximum value at the Hayman site. These results were unexpected because the area of the Hayman watersheds (0.03 km^2) was much smaller than those studied by Kunze and Stednick (2006) (2 to 4 km^2) and Moody and Martin (2001*a*) (27 km^2, 21 km^2 of which had burned). However, when the peak flow rates were normalised by the rainfall intensity, the peak flow per unit of I_{30} for the Hayman site (0.18 $m^3 s^{-1} km^{-2}$ per unit of I_{30}) was similar to the 0.09 $m^3 s^{-1} km^{-2}$ per unit of I_{30} measured by Kunze and Stednick (2006) and the 0.2 $m^3 s^{-1} km^{-2}$ per unit of I_{30} derived from Moody and Martin (2001*a*) data. This comparison suggests that the rainfall intensity, despite its lack of significance in our statistical models of runoff and peak flow, plays an important role in the post-fire peak flow response.

The number of years after burning was a significant covariate for the log-transformed sediment yields, which indicates that post-fire sediment yields decrease significantly as time after burning increases. Previous studies have suggested that post-fire sediment yields generally decrease by an order of magnitude with each post-fire year and that burned areas recover with no measurable fire-influenced erosion by the fourth or fifth post-fire year (Robichaud and Brown 2000; Robichaud *et al*. 2000). However, the North 25, Mixing, and Cannon site data (Table 5) show that given a storm with a large enough intensity, measurable erosion can occur in post-fire years 4 and 5. Also, the sediment yields in the controls at the North 25, Mixing, and Valley Complex sites did not decline by an order of magnitude in the second post-fire year as compared with the first post-fire year (Table 7). The recovery period required for post-fire runoff, peak flows, and sediment yields may be longer than previously reported and needs further evaluation.

Conclusions

Rainfall characteristics varied widely among the regions where post-fire matched small watershed sites were located. In all locations, except for the Mixing site (south-western California), short-duration, high-intensity rainfall events produced most of the measured runoff and sediment yields. Even in areas where snowmelt dominates the hydrologic cycle (North 25, central Washington; Valley Complex, western Montana; and Fridley, southern Montana), rainfall events, not snowmelt events, controlled the erosional response. At the Mixing site, long-duration rain events produced most of the runoff and erosion.

Runoff, peak flows, and sediment yields were generally lower from the LEB-treated watersheds than the control watersheds, and these differences were driven by the watersheds' responses to small rain events (storms with less than a 2-year, 10-min return interval). There was no detectable treatment effect for large rain events with a 2-year or greater return interval at the 10-min duration.

LEBs can have several defects – both from improper installation and from degradation over time – that reduce their effectiveness. The most commonly observed defect in the present study was logs being installed or later moved off-contour, which often resulted in scouring and rill formation.

The large variation in runoff, peak flows, and sediment yields among sites suggests that post-fire assessment teams and land managers should carefully consider regional climatic, topographic, and ecological conditions when deciding whether to apply LEBs as a post-fire erosion mitigation treatment. Most post-fire assessment teams use rain events with high return periods as design storms for hydrologic predictions and evaluation of treatment alternatives. These results suggest that LEBs will not reduce runoff or sediment yields from rain events that have return intervals of 2 years or greater. Thus, assessment teams should carefully consider the probability of exceeding the storm size in which the LEB treatment could be effective.

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