Postfire Rehabilitation of the Hayman Fire

Peter Robichaud, Lee MacDonald, Jeff Freeouf, Dan Neary, Deborah Martin, Louise Ashmun

Introduction

Our team was asked to analyze and comment on the existing knowledge and science related to postfire rehabilitation treatments, with particular emphasis on the known effectiveness of these treatments. The general effects of fire on Western forested landscapes are well documented (Agee 1993; DeBano and others 1998; Kozlowski and Ahlgren 1974) and have been thoroughly discussed in other chapters of this report. However, postfire erosion and rehabilitation treatment effectiveness have not been studied extensively.

The first part of this chapter describes the postfire conditions, as identified by the Burned Area Emergency Rehabilitation (BAER) team, and the subsequent BAER team recommendations for rehabilitation treatment. The next sections describe the different treatments, where they were applied on the Hayman Fire burn area, and the current knowledge of treatment effectiveness. The recommendations for monitoring treatment effectiveness will answer the specific question, "What types of monitoring protocol and reports should Forest Service and other jurisdictions put in place to continue to learn from this fire?" and outline a general process for monitoring postfire rehabilitation efforts. This is followed by a description of the sites currently established within the Hayman Fire burned area to evaluate the effectiveness of various rehabilitation treatments. The need to establish control sites (burned but not treated) to provide a basis for comparison and monitor natural recovery is also discussed. The final section identifies the knowledge gaps that need to be addressed to guide the selection of postfire rehabilitation treatments on future fires in the Colorado Front Range and similar environments.

BAER Team Report of Postfire Conditions and Predictions for the Hayman Fire Area

The Burned Area Report filed by the BAER team describes the hydrologic and soil conditions in the Hayman Fire area as well as the predicted increase in runoff, erosion, and sedimentation. The predictions were then evaluated in combination with both the onsite and downstream values at risk to determine the selection and placement of emergency rehabilitation treatments (USDA Forest Service 2002). The BAER team used data from nearby fires, erosion prediction tools, and professional judgment to make these predictions and recommendations.

Burn Severity

The BAER team burn severity map was derived from a Spot 4 satellite image and is based primarily on overstory tree mortality (fig. 1). However, burn severity is the result of several interacting variables that are reflected to varying degrees in the overstory tree mortality. Hungerford (1996), building on earlier work by Ryan and Noste (1983), developed a general burn severity classification based on the postfire appearance of litter and soil (table 1). In the Hayman Fire area, there are many areas where the ground conditions reflect moderate burn severity in Hungerford's scheme while the overstory, with all the twigs and needles consumed, reflects a high severity burn. This is less problematic than it might first appear, as the lack of needlecast indicates: (a) minimal protection of soil particles to detachment by rainsplash and overland flow; (b) no needles to moderate surface soil temperatures and facilitate soil moisture storage (which may lead to longer revegetation recovery times); and (c) no needles to immediately add organic matter. The lack of needles, combined with a thin but strong water repellent surface layer, will likely lead to rapid runoff and substantial soil erosion during intense storms.

The BAER team did considerable ground truthing to compare ground cover and soil conditions with canopy conditions before deciding that the satellite burn severity map, while based on overstory effects, is roughly aligned with the expected hydrologic and erosion response. Given the lack of time and resources to develop more detailed or direct evaluation of soil conditions, the burn severity map created from satellite data is a

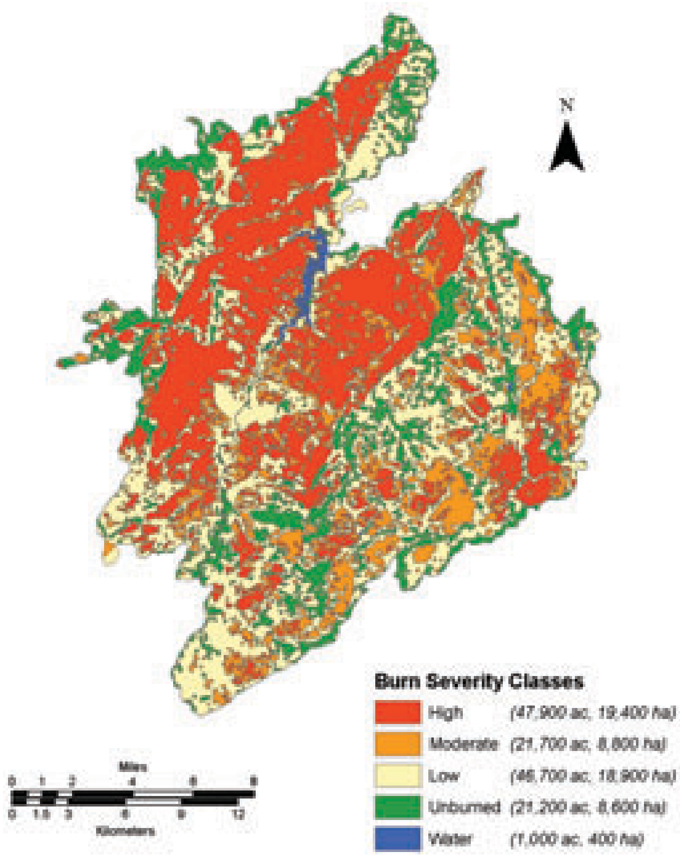

Figure 1—The burn severity map of the Hayman Fire area as developed by the BAER Team.

reasonable tool for evaluating postfire conditions, predictive modeling, and recommending rehabilitation treatments (fig. 1). From this image, the BAER team classified approximately 48,000 acres (35 percent) as high severity, 22,000 acres (16 percent) as moderate severity, 47,000 acres (34 percent) as low severity, and 21,000 (15 percent) as unburned. The team also decided that moderate severity burn areas would respond to future rain events in much the same way as high severity burn areas; consequently, 50 percent of the moderate severity burn areas were considered for postfire rehabilitation treatment.

Hydrology

Soils, vegetation, and litter are critical to the functioning of hydrologic processes. Forested watersheds with good hydrologic conditions (greater than 75 percent of the ground covered with vegetation and litter) sustain stream baseflow conditions for much or all of the year and produce little sediment. Under these conditions 2 percent or less of the rainfall becomes surface runoff, and erosion is low (Bailey and Copeland 1961). Fire can destroy the accumulated forest floor layer and vegetation and greatly alter infiltration rates by exposing soils to raindrop impact and creating water repellent conditions (DeBano and others 1998). Severe fires may create poor hydrologic conditions (less than 10 percent of the ground surface covered with plants and litter); surface runoff can increase over 70 percent; and erosion can increase by three orders of magnitude (DeBano and others 1998). Poor hydrologic conditions are likely to occur in any area with high, or in some cases moderate, burn severity. Given that 35 percent of the Hayman Fire area was classified high burn severity and another 16 percent was classified moderate burn severity, poor hydrological conditions can exist in approximately half of the burned area.

In the Intermountain West, high-intensity, short-duration rainfall is relatively common (Farmer and Fletcher 1972). After fires such storms have been shown to generate high stream peakflows and high erosion rates (DeBano and others 1998; Neary and others 1999; Moody and Martin 2001a). Thirty-minute rainfall intensities (I_{30}) greater than 0.4 inches per hour (10 mm per hour) exceeded the average infiltration rate and caused surface runoff after the Buffalo Creek Fire (Moody and Martin 2001a) and the Bobcat

Table 1—Burn severity classification based on postfire appearances of litter and soil and soil temperature profiles (Hungerford 1996; DeBano and others 1998).

Soil and litter parameter	Burn severity: Low	Burn severity: Moderate	Burn severity: High
Litter	Scorched, charred, consumed	Consumed	Consumed
Duff	Intact, surface char	Deep char, consumed	Consumed
Woody Debris - Small	Partly consumed, charred	Consumed	Consumed
Woody Debris - Logs	Charred	Charred	Consumed, deep char
Ash Color	Black	Light colored	Reddish orange
Mineral Soil	Not changed	Not changed	Altered structure, porosity, etc
Soil Temp. at 0.4 in (1 cm)	<120 °F (<50 °C)	210-390 °F (100-200 °C)	>480 °F (>250 °C)
Soil Organism Lethal Temp.	To 0.4 in (1 cm)	To 2 in (5 cm)	To 6 in (16 cm)

Fire (Kunze 2003) in the Colorado Front Range. The loss of ground cover, combined with water repellent soils, will cause flood peaks to arrive faster, rise to higher levels, and entrain significantly greater amounts of bedload and suspended sediments. The thunderstorms that produce these rainfall intensities may be quite limited in extent but can produce profound localized flooding effects (Moody and Martin 2001a, Kunze 2003). Observations to date indicate that flood peakflows after fires in the Western United States can range up to three orders of magnitude greater than prewildfire conditions (table 2). As a result of the Hayman Fire, peak flows within the watersheds covered by the burned area are expected to occur more rapidly and be much greater than prefire magnitudes, but specific amounts are difficult to predict and will vary with the magnitude and season of the individual storm event.

Runoff Modeling

The BAER team predicted runoff volumes by applying the National Resource Conservation Service (NRCS) curve number model to a design storm. The resulting runoff depths were converted to runoff by using the triangular unit hydrograph model on each watershed. This approach did not involve any channel routing (Hawkins and Greenberg 1990).

Design Storm and Runoff Predictions—The design storm selected to evaluate prefire and postfire runoff was the 25-year, 1-hour storm over an area of 5.0 mi^2 (13 km^2). The predicted precipitation for this event is 1.0 inch (25 mm) in 1 hour. The distribution of rainfall intensities over the 1-hour period (33 percent of the rain falls in the first 5 minutes with declining intensity for the rest of the hour) was based on local information of short duration rainfall relations (Arkell and Richards 1986). This results in a design storm that looks like a typical summer thunderstorm for the Hayman region (fig. 2).

The runoff WILDCAT4 model (Hawkins and Greenberg 1990) was used by the BAER team to estimate pre- and postfire runoff hydrographs from 84 watersheds (average size 3 mi^2, 7.8 km^2). The assumed curve numbers to predict runoff volumes for various watershed conditions were: rock = 90, unburned = 80, low severity = 85, and moderate and high severity = 95 (Kuyumjian and others 2002).

The models were applied to the 84 watersheds, and substantial increases in peak flow events were predicted for those watersheds where a high percentage of the area was burned at moderate to high severity. The average prefire predicted peak flow was 75 cfs mi^{-2} (0.8 m^3 s^{-1} km^{-2}) and the predicted postfire peak flow was 290 cfs mi^{-2} (3.1 m^3 s^{-1} km^{-2}). The distribution of postfire predicted peak flows shows half of the watersheds falling between 100 to 300 cfs mi^{-2} (1.1 to 3.3 m^3 $s^{-1}km^{-2}$). Thirty-one of the 84 watersheds were above this range with predicted peak flows from 10 watersheds exceeding 500 cfs mi^{-2} (5.4 m^3 s^{-1} km^{-2}) and three of these exceeding 600 cfs mi^{-2} (6.5 m^3 s^{-1} km^{-2}) (fig. 3). Average predicted peak flows were nearly 300 cfs mi^{-2} (3.3 m^3 s^{-1} km^{-2}) for three main areas of the fire: (1) upstream of Cheesman Reservoir, (2) downstream of Cheesman on the west side of the South Platte River, and (3) downstream of Cheesman on the east side of the South Platte River (fig. 4 and table 3) (Kuyumjian and others 2002).

Model Validation—The design storm for the Hayman Fire has an I_{30} of 1.7 inch per hour (43 mm per hour), which is similar to the higher intensities recorded by Moody and Martin (2001a) after the Buffalo Creek Fire. An I_{30} of 2.0 inch per hour (50 mm per hour) yielded 480 cfs mi^{-2} (5.2 m^3 s^{-1} km^{-2}) and an I_{30} of

Table 2—Peakflow responses to wildfires in conifer forest habitats. The areas most similar to the Hayman Fire area are indicated in bold print (after Robichaud and others 2000).

Location	Treatment	Peakflow increase factor	Reference
Ponderosa pine, AZ	Wildfire	+5 Summer +15 Summer +10 Fall +0 Winter	Rich 1962
Ponderosa pine, AZ	Wildfire	+96	Campbell and others 1977
Ponderosa pine, AZ	Wildfire, Moderate Wildfire, Severe	+23 +406	DeBano and others 1996
Ponderosa pine, NM	Wildfire	+160	Bolin and Ward 1987
Mixed Conifer, AZ	Wildfire	+7	Neary and Gottfried 2001
Mixed Conifer, CO	**Wildfire**	**+140**	**Moody and Martin 2001**
Mixed Conifer, CO	**Wildfire**	**+10**	**Kunze 2003**

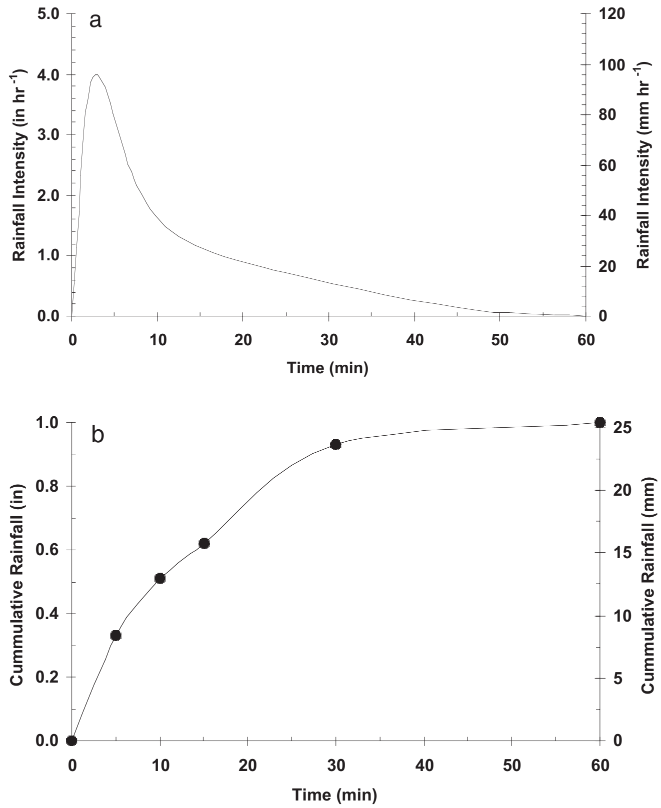

Figure 2—In order to model typical convective storm events and predict subsequent runoff, the BAER Team used NOAA Atlas #2 and rainfall data to develop the design storm of 1.0 inch (25 mm) in 1 hour. (a) Design storm intensity over time. (b) Cumulative rainfall over one hour. [Note: 33 percent of the total rain falls in the first 5 minutes and over 90 percent falls in the first 30 minutes]

1.8 inch per hour (45 mm per hour) yielded 300 cfs mi^{-2} (3.2 m^{3} s^{-1} km^{-2}) 2 years after the fire (Moody and Martin 2001a). The WILDCAT4 model used in the Hayman Fire area predicted unit area flows that are consistent with measured precipitation events and the resulting runoffs from the Buffalo Creek Fire (Kuyumjian and others 2002).

Soils

The landforms of the Hayman Fire area are dominantly steep mountain slope lands (15 to 80 percent) in highly dissected V-shaped valleys. Douglas fir (*Pseudotsuga menziesii*)/mountain muhly (*Muhlenbergia montana*) and ponderosa pine (*Pinus ponderosa*)/slimstem muhly (*Muhlenbergia filiformis*) are the dominant vegetation types. The parent material on the Hayman Fire area is Pikes Peak granite, which

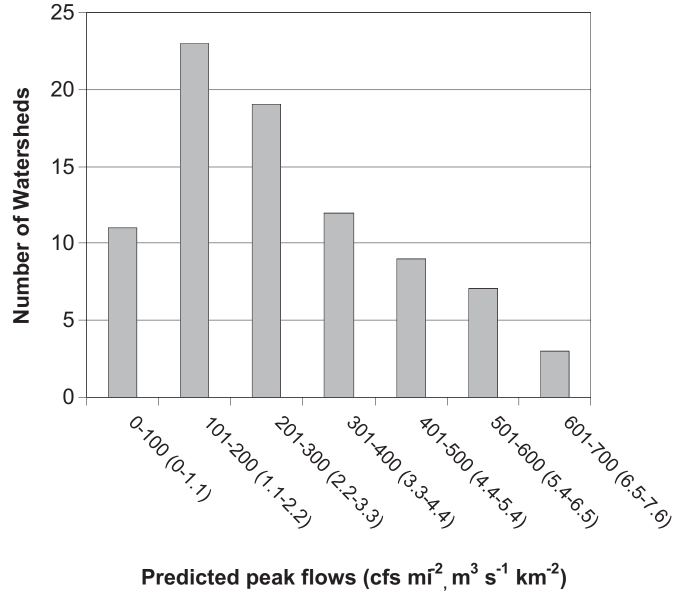

Figure 3—Distribution of predicted peak flows for the 84 watersheds within the Hayman Fire area for a design storm of 1.0 inch (25 mm) in 1 hour.

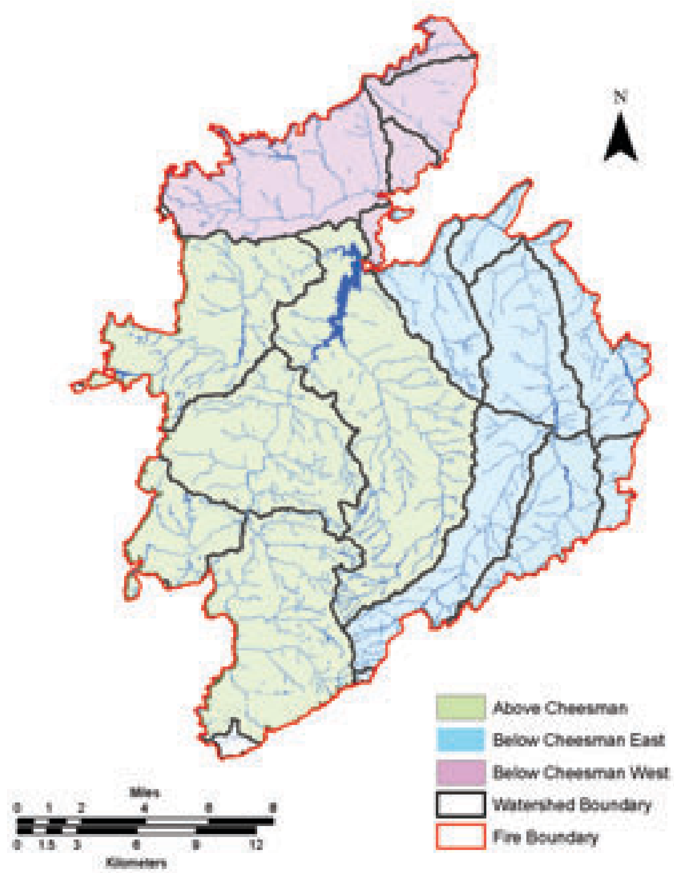

Figure 4—The three general areas used by the BAER team to determine potential postfire runoff and sediment delivery.

Table 3—Average predicted postfire peakflows from a design storm of 1.0 inch (25 mm) in 1 hour as modeled by the Hayman Fire BAER Team.

General area description	Average watershed size[a]		Average predicted peakflow	
	mi²	*km²*	*cfs mi⁻²*	*m³s⁻¹ km⁻²*
Above Cheesman Reservoir	3.2	(8.3)	290	(3.2)
Below Cheesman Reservoir (West)	3.1	(8.1)	292	(3.2)
Below Cheesman Reservoir (East)	2.4	(6.2)	297	(3.2)

[a] Average size of modeled watershed within the selected area.

weathers to fine gravel and coarse sand in the soil profile. The coarse-textured parent material provides a moderately acidic substrate for soil development. The soils developed from Pikes Peak granite are highly susceptible to erosion, sheetwash, rilling and gullying (John 2002).

The soils in the area consist predominantly of two soil series, Sphinx and Legault. Rock outcrops (15 percent of the total area) dominate in some areas, and alluvial soils are found in most valley bottoms. The Sphinx soils are coarse-textured, shallow and somewhat excessively drained. The surface layer is gravelly coarse sandy loam. Permeability is rapid, and the available water capacity is low. Runoff is moderate to rapid, and the hazard of water erosion is moderate to severe depending on slope. The Legault soils are dark grayish brown, very gravelly coarse sandy loam. It is found on north-facing aspects and at higher elevations. Permeability is moderately rapid, and the available water capacity is very low. Runoff is rapid, and the hazard of erosion is moderate to severe depending on slope (John 2002).

Erosion

Nearly all fires increase sediment yield, but wildfires in steep terrain produce the greatest amounts (12 to 165 t ac^{-1}, 28 to 370 Mg ha^{-1}) (table 4). Postfire channel incision and gully formation can be important sources of sediment in the Colorado Front Range (Moody and Martin 2001a). Field studies initiated after the Hayman Fire are showing that the increase in surface runoff has led to channel initiation in formerly unchannelled swales as well as incision and gullying in existing channels (Libohova and MacDonald 2003). Hence, a full evaluation of the effects of wildfires on erosion rates includes an assessment of both hillslope erosion rates and changes in the extent and size of the stream channel network. The data and models needed to predict channel incision and erosion are not currently available, so this component was not

Table 4—First-year sediment losses after wildfires in conifer forest habitats (after Robichaud and others 2000).

Location	Treatment	Sediment loss		Reference
		t ac⁻¹	*Mg ha⁻¹*	
Ponderosa Pine, AZ	Control	0.001	0.003	Campbell and others 1977
	Wildfire	0.6	1.3	
Ponderosa Pine, AZ	Wildfire, Low	0.001	0.003	DeBano and others 1996
	Wildfire, Moderate	0.009	0.02	
	Wildfire, Severe	0.7	1.6	
Mixed Conifer, AZ	Control	<0.0004	<0.001	Hendricks and Johnson 1944
	Wildfire, 43% Slope	32	72	
	Wildfire, 66% Slope	90	200	
	Wildfire, 78% Slope	165	370	
P. pine/Doug. fir, ID	Wildfire	4	9	Noble and Lundeen 1971
P. pine/Doug. fir, ID	Clearcut and Wildfire	92	210	Megahan and Molitor 1975
P. pine/Doug. fir, OR	Wildfire, 20 % Slope	0.5	1.1	Robichaud and Brown 1999
	Wildfire, 30 % Slope	1.0	2.2	
	Wildfire, 60 % Slope	1.1	2.5	
Ponderosa Pine, CO	Wildfire, 25 to 43 % Slope	3 to 4	8 to 10	Benavides-Solorio 2003

included in the postfire predictions from the BAER team.

Hillside erosion rates are also difficult to predict with accuracy. Studies and observations indicate that high severity fires in the Colorado Front Range can greatly increase runoff and erosion rates (Morris and Moses 1987; Moody and Martin 2001a; Benavides-Solorio 2003). However, these rates are highly variable. Soil erosion after prescribed burns has been shown to vary from under 0.4 to 2.6 t ac^{-1} yr^{-1} (1 to 6 Mg ha^{-1} yr^{-1}), and in wildfires from 0.2 to over 49 t ac^{-1} yr^{-1} (0.4 to over 110 Mg ha^{-1} yr^{-1}) (Megahan and Molitor 1975; Noble and Lundeen 1971; Robichaud and Brown 2000) (table 4). There are few data available describing the controlling factors that account for the magnitude of runoff and erosion increases, or the rate at which the elevated processes recover to background levels, although this situation is beginning to change (Benavides-Solorio and MacDonald 2001; Benavides-Solorio 2003).

Existing data and observations indicate that erosion on burned areas typically declines in subsequent years. After a wildfire in eastern Oregon, Robichaud and Brown (2000) reported first-year erosion rates of 0.5 to 1.1 t ac^{-1} (1.1 to 2.5 Mg ha^{-1}), decreasing by an order of magnitude in the second year, and to no sediment by the fourth year. Erosion rates from high severity sites in the Buffalo Creek Fire declined to background levels within 3 years (Moody and Martin 2001b). Benavides-Solorio (2003) indicates erosion rates on the Colorado Front Range should recover in 4 to 6 years. To help limit damage to soil and watershed resources, postfire rehabilitation treatments that reduce erosion in the first years are important.

Given the uncertainties in predicting postfire erosion, the BAER team used erosion data from the nearby Turkey Creek and Buffalo Creek Fires to estimate the postfire erosion rate for the areas burned at moderate and high severity. The Water Erosion Prediction Project (WEPP) model, as modified for disturbed forest land (Elliot and others 2001), was used to predict the erosion rates for the low severity and unburned areas. Field assessments were used to verify the conditions and assumptions used in the modeling. The resulting predicted first year erosion rates for each burn severity class is shown in table 5. The estimated first year erosion rate by the BAER team for the Hayman Fire area is 43 t ac^{-1} (96 Mg ha^{-1}), based on a weighted average of the erosion rates by severity class and acreage in each group (John 2002).

Water Quality and Sedimentation

The South Platte River flows from southwest to the northeast through the interior of the Hayman Fire burn area. Eleven sixth-level watersheds were affected by the fire (fig. 4). The typical drainage area of a sixth-level stream is 10,000 to 30,000 acres (4,000 to 12,000 ha) and these include perennial tributaries such as Brush Creek, Fourmile Creek, Goose Creek, Horse Creek, Saloon Creek, Turkey Creek, West Creek, and Wigwam Creek. Cheesman Reservoir is a major impoundment on the South Platte River near the center of the burn. Strontia Springs Reservoir is another impoundment on the South Platte River downstream of the burned area. The Denver Water Board owns and operates these reservoirs as water supply facilities for the Denver metropolitan area. Approximately 44 percent of the burned area drains into the South Platte River downstream of Cheesman Reservoir, while roughly 56 percent of the burned area drains directly into Cheesman Reservoir or the South Platte River upstream of the reservoir.

During postfire storm events in August and September 2002, organic carbon, ash, and sediment increases occurred within several smaller drainage basins as well as within the South Platte River above and below Cheesman Reservoir. The first postfire storms mobilized sediment, which will continue to be mobilized with successive events.

The sediment delivery potential in the Hayman Fire area is based on postfire monitoring of the Buffalo Fire (Moody and Martin 2001a), which demonstrated that approximately 15 ac-ft (24,000 yd^3, 18,500 m^3) of sediment was delivered to Strontia Springs Reservoir for each square mile of burned area over the 5 years following the fire. This value—15 ac-ft mi^{-2} (24,000 yd^3 mi^{-2}or 71,000 m^3 km^{-2}) over the 5-year recovery

Table 5—Predicted first-year erosion rates by burn severity class as determined by the Hayman Fire BAER team.

Burn severity	Area			Erosion rate	
	acres	*ha*	*percent*	*tons/acre^{-1}*	*Mg/ha^{-1}*
Unburned	21,200	(8,600)	15	0.5	(1.1)
Low	46,700	(18,900)	34	22	(50)
Moderate	21,700	(8,800)	16	70	(160)
High	47,900	(19,400)	35	70	(160)

period—provides an upper bound for sediment export because Buffalo Creek runoff and sediment transport were influenced by an extreme precipitation event immediately after the fire. Given the Hayman Fire area of approximately 137,600 acres (215 mi^2 or 560 km^2) the potential upper bound of sediment volume delivered to streams may be as great as 3,500 ac-ft (5.6 million yd^3, 4.3 million m^3) over the 5-year recovery period (USDA Forest Service 2002).

The sediment delivery potential was estimated for the three main areas of the burn: (1) the area upstream of Cheesman Reservoir dam; (2) the watershed area downstream of Cheesman on the west side of the South Platte River; and (3) the watershed area downstream of Cheesman on the east side of the South Platte River (table 6 and fig. 4). Assuming a 5-year sediment yield of 15 ac-ft mi^{-2} (24,000 yd^3 mi^{-2}, 71,000 m^3 km^{-2}), approximately 1,500 ac-ft (2.4 million yd^3, 1.8 million m^3) of sediment could enter the South Platte River below Cheesman Reservoir over the 5 years. Potentially, 1,950 ac-ft (3.1 million yd^3, 2.4 million m^3) of sediment could enter the South Platte River and Cheesman Reservoir above the dam during the 5-year recovery period (USDA Forest Service 2002).

Cheesman Reservoir does not appear to be at risk to filling in with sediment. The maximum expected sediment delivery to Cheesman Reservoir over the first 5 years following the fire is 1,950 ac-ft (3.1 million yd^3 or 2.4 million m^3). Since the storage capacity of Cheesman Reservoir is approximately 79,800 ac-ft (130 million yd^3, 98 million m^3), the sediment delivered as the result of the Hayman Fire should be less than 3 percent of the reservoir storage capacity.

The storage capacity of Strontia Springs Reservoir is about 7,600 acre-ft (12.3 million yd^3 or 9.4 million m^3). A maximum of about 1,500 acre-ft (2.5 million yd^3, 1.9 million m^3) of sediment could enter the South Platte River below Cheesman; however, only a portion of that is expected to be routed directly to Strontia Springs Reservoir. The South Platte River flows for approximately 20 to 25 miles (32 to 40 km) from Cheesman Reservoir downstream to Strontia Springs, and it is a relatively low gradient meandering stream with a fair amount of in-channel and near-channel sediment storage capacity. This section of the river should reduce the amount of sediment that is delivered to Strontia Springs Reservoir. However, other large fires (Buffalo Creek, 1996; Hi Meadow Fire, 2000; Schoonover, 2002) have occurred in this drainage over the last 6 years, contributing significant sediment to this reservoir. Strontia Springs Reservoir was being dredged because of excess sedimentation when the Hayman Fire occurred (USDA Forest Service 2002).

Risk Assessment

The values at risk as identified by the BAER Team include the following:

Increased Flood Flows—Stream flows will increase after the fire due to a combination of the loss of ground cover, decreased infiltration, a reduction in evapotranspiration, reduced water storage within the soil, and snowmelt modification. Moderate to high severity burn areas in high precipitation zones will produce the largest increases in runoff. The increased risk of flash flood flows will diminish the safety of recreational travel and camping. An increase in flood flows may temporarily prevent access to private property and recreational opportunities.

Ponds/Dams—Several private ponds exist in the West Creek and Trout Creek drainages. Both in-channel and within floodplain ponds exist. Postfire flows may be a combination of water and debris in which jams form and break, causing surges or slugs of material down the stream channels filling ponds and threatening earthen dams.

Debris Flow Potential—Increased stream flows may be combined with debris flows of floatable and transportable material. Recent experiences from the Cerro Grande, East Fork Bitterroot, Clover-Mist, and

Table 6—Potential sediment delivery to streams as modeled by the Hayman Fire BAER team for a 5 year recovery period.

General area description	Area[a]				Potential sediment delivery to streams[b]	
	acre	*ha*	*mi^2*	*km^2*	*acre-feet (5 year)$^{-1}$*	*m^3 (5 yr)$^{-1}$*
Above Cheeseman Reservoir	83,000	(34,600)	130	(340)	1,950	(2,400,000)
Below Cheesman Reservoir (west)	21,700	(8,800)	34	(90)	510	(600,000)
Below Cheesman Reservoir (east)	43,700	(17,700)	68	(180)	1,020	(1,300,000)

[a] Approximate area, includes some unburned area outside of fire perimeter.

[b] Based on postfire monitoring of the Buffalo Creek Fire (Moody and Martin 2001) . The potential rate of 15 ac-ft mi^{-2} (7,100 m^3 km^{-2}) during the 5-year recovery period includes storms of higher intensity than the design storm.

Buffalo Creek Fires demonstrate that debris flows have greater potential of occurrence after high severity burns. Debris flows may impact road crossings, private property, and channel stability.

Water Quality—Trout Creek and the South Platte River above Cheesman Reservoir are on the 1998 Colorado 303(d) list for sediment. Section 303(d) of the Clean Water Act requires that States or the EPA set total maximum daily load (TMDL) for water bodies that fail to comply with the standards. A TMDL stipulates how much of a particular pollutant a water body may receive and still conform to water quality standards (Colorado WQCD 2002). Goose Creek, Horse Creek, Taryall Creek, and Trail Creek are on the 1998 Colorado Monitoring and Evaluation (M&E) list for sediment. The M&E list is intended to identify and track water bodies for which there is some evidence of nonattainment of water quality standards, but for which there is not adequate documentation to support inclusion on the 303(d) list (Colorado WQCD 2002).

The South Platte River is the conveyance system for the public water supply of the Metropolitan Denver area. There are also domestic wells within and around the burned area that may be impacted. In addition, reduced water quality within the burned area and downstream will affect esthetics and recreational use.

Threats to Aquatic Life—Ash, sediment, and other water quality factors may impact aquatic resources. The South Platte River is a significant and popular sport fishery.

BAER Team Treatment Objectives

The BAER Team delineated specific treatments and application locations (USDA Forest Service 2002). The BAER Team report included the following treatment objectives:

- Reduce erosion by providing ground cover and increase infiltration by scarifying the soil surface. Seeding done at appropriate locations and application methods will also increase ground cover.
- Reduce impacts to the Denver water supply reservoirs and the water quality-listed streams.
- Protect targeted structures that are downslope from National Forest burned acreage.
- Protect roads and crossings from flood flows.
- Spot-treat noxious weeds within the fire area to reduce the threat of significant expansion and invasion of noxious weed species.
- Straw bale placement to divert anticipated storm flows away from two sensitive heritage sites.
- Monitor erosion and sediment delivery in treated areas to evaluate success of BAER treatments.

BAER Team Treatment Recommendations

The BAER team recommended a variety of emergency rehabilitation treatments based on the estimated runoff and erosion rates as well as the risks summarized above. Included in the BAER team recommendations is the area of each treatment (fig. 5). The large-scale logistics of emergency rehabilitation treatment application means that adjustments must accommodate unforeseen circumstances during the application process. The Hayman Fire was no exception, as the recommended treatment areas and associated costs changed throughout the application process (table 7). Rationales for the changes from the original BAER treatment plan were delineated in the revised Burned Area Report submitted on August 21, 2002. These explanations are summarized, in italics, at the end of the treatment descriptions that follow (USDA Forest Service 2002).

The final figures for 2002 indicate that approximately $16.5 million were spent to treat 45,500 acres (nearly 45 percent) of the 100,000 acres of National Forest land that burned (table 7). Approximately $2.5 million to $5 million are allocated for 2003 to complete these rehabilitation treatments. Unless otherwise noted, treatment figures refer to National Forest land only and do not include any treatment on the 16,300 acres of private and State owned land that burned (fig. 5).

Land Treatments—

- *Ground-based hydromulching with seed* (fig. 6), for 1,500 acres (600 ha). Truck-mounted hydromulching was done from existing roads within high severity burn areas. Treatment occurred within 300 feet (90 m) either side of 25 miles (40 km) of road. Ground-cover amounts were 2000 lb per acre (2.24 Mg per ha). Seed mix and seed application rate were as described in table 8.
- *Aerial hydromulching with seed* (fig. 7, 8, 9), for 1,500 acres (600 ha). Aerial hydromulching was done on high severity burn areas draining to the South Platte River below Cheesman dam that could not be reached by existing roads. The focus was on ridge-tops and upper one-third of 20 to 60 percent slopes. Application rate was 2,000 lb per acre (2.24 Mg per ha), and the mulch and tackifier was suitable for 20 to 60 percent slopes. Seed mix and seed application rate were as described in table 8.
- *Aerial dry mulching with seed* (fig. 10, 11), for 7,700 acres (3,100 ha). Aerial dry mulching with

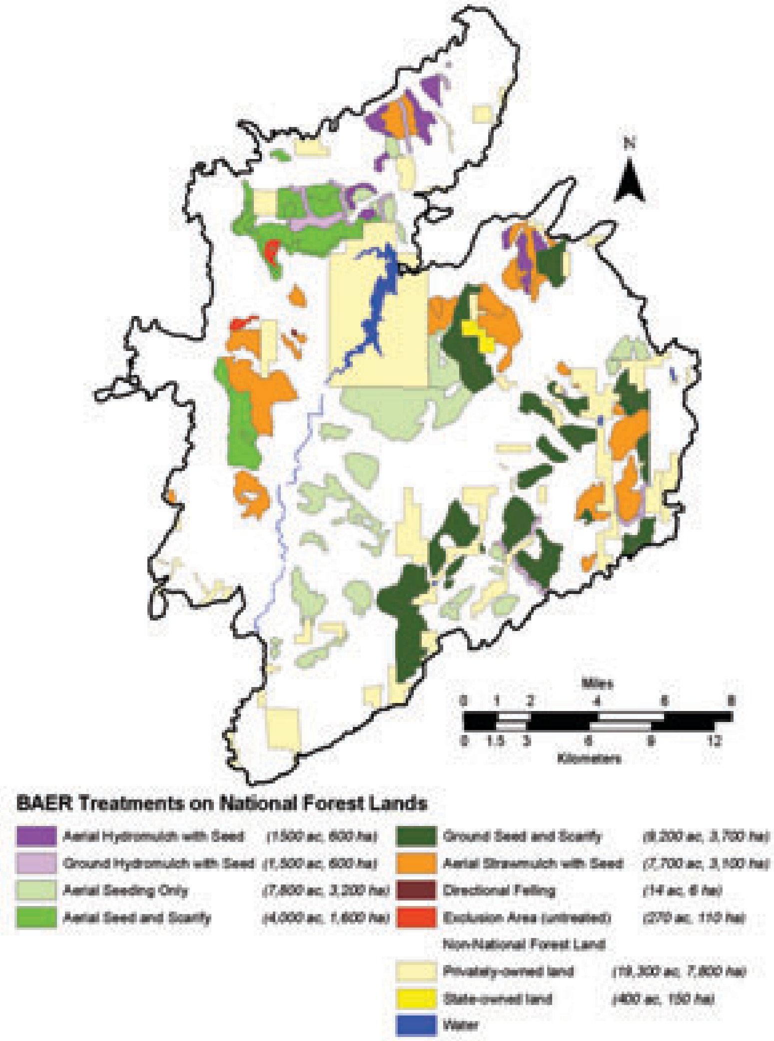

Figure 5—Hayman postfire rehabilitation treatment map for National Forest lands.

seed was applied to high severity fire areas above Cheesman dam that cannot be reached by existing roads. Focus was on ridge-tops and the upper one-third of the slopes. Application rate was 2,000 lb per acre (2.24 Mg per ha). Seed mix and seed application rate were as described in table 8. *A total 4,000 acres of treatments originally intended for the more costly aerial hydromulching were changed to the dry mulching treatment. The cost savings provided for an additional 5,500 acres of dry mulch treatment on high severity burn areas. The contract was terminated for convenience to the government prior to the contract completion.*

- *Mechanical scarification by all terrain vehicles (ATV), with seed* (fig. 12), for 9,200 acres (3,700 ha). Scarification and seeding occurred on selected high severity-burn areas on slopes less than 20 percent. Areas were treated with a chain-link harrow with 4 inches (10 cm) teeth pulled behind an ATV on the contour to break up the water repellent soil layer and thereby increase infiltration rates. Seed mix and seed application rates were as described in table 8. *Part of the acreage initially identified for ATV scarification was found to be too steep and dissected for safe operation.*
- *Hand scarification with seed* (fig. 13), for 4,000 acres (1,600 ha). Hand scarification and seeding was done on selected high severity burn areas where slopes were too steep (greater than 20 percent) for ATVs. The treatment was done using hand-rakes (McLeods) followed by aerial or hand seeding. Seed mix and seed application rate were as described in table 8. *These acres were initially*

Table 7—Postfire emergency rehabilitation treatment costs for the Hayman Fire in 2002. Note the changes in treatment acreages from the initial assessment to the actual acreages treated. An additional $3 to 5 million will be spent in 2003 to complete the BAER treatment application.

	National Forest System lands					
Land treatments	Units	Unit cost	Recommended units		Actual units treated	Treatment cost
		$	*#* July 5, 2002	*#* August 7, 2002	*#*	*$*
Road Hydromulching	Acres	950	1,500	1,500	1,500	1,400,000
Aerial Hydromulching	Acres	3,000	5,500	1,500	1,500	4,500,000
Aerial Dry Mulching	Acres	728	4,500	15,000	7,700	5,610,000
Mechanical Scarification	Acres	50	15,000	13,000	9,200	460,000
Hand Scarification	Acres	240	None	4,000	4000	960,000
Aerial Seeding	Acres	18	None	19,000	19,300	350,000
Seed	Pound	0.29			2,000,000	580,000
Colorado Cares	Project	1	1	1	1	16,500
Heritage Site Protection	Sites	670	2	2	2	1,300
Noxious Weed Treatments	Acres	100	210	370	370	37,000
NFS-Above Private Land Treatments	Sites	NA	6	6	6	12,000
Flood Warning Signs	Project				1	2,600
					Subtotal	$14,000,000
Road and trail treatments						
Maintenance and Closures	Total				1	190,000
					Subtotal	$190,000
BAER evaluation						
Team Costs and Helicopter Time	Total				1	136,000
					Subtotal	$136,000
Monitoring						
Noxious Weed Monitoring	Project				1	25,000
					Subtotal	$25,000
Other						
Implementation Overhead Team	day	24,000	45		86	2,100,000
					Subtotal	$2,100,000
					TOTAL	$16,500,000

Figure 6—Ground-based application of hydromulch.

Table 8—Seed mix used for aerial seeding, aerial hydromulch and ground hydromulch applications after the Hayman Fire.

Annual seed mix	Mix amount	Broadcast rate		Seeds	
	percent	*lbs* ac^{-1}	*kg* ha^{-1}	# ft^{-2}	# m^{-2}
Barley (*Hordeum vulgare*)	70	70	(80)	26	(280)
Triticale (*xTriticosecale rimpaui*)	30				

Figure 7—Aerial hydromulch staging area.

Figure 8—Helicopter with tanks for hydromulch slurry.

Figure 9—Aerial application of hydromulch.

Figure 10—Aerial dry mulch staging area. Straw bales on cargo nets ready for helicopter transport.

Figure 11—Aerial dry mulch being applied.

Figure 12—Mechanical scarification with an ATV pulling a chain harrow.

designated for mechanical scarification using ATV's pulling harrows; however, safety issues for the ATV's made hand scarification a better a option.

- *Seeding* for 25,000 acres (10,000 ha). Seeding was done on all areas that received scarification or mulch treatments. To ensure the quality of seed used in this rehabilitation effort, the Forest Service obtained all of the seed and made sure that the seed had been tested for noxious weed content and inert matter within the past 120 days. All seed was certified noxious weed-free mixes of 70 percent barley (*Hordeum vulgare*) and 30 percent triticale (*xTriticosecale rimpaui*) seed, nonpersistent annual grasses. *Aerial seeding was not initially planned. However, seeding was added shortly after the initial assessment and fixed wing aircraft were used to seed areas not seeded by hand or in conjunction with hydromulch applications. Approximately 5,300 acres (2,100 ha) that were scarified were aerial seeded to expedite completion of that treatment. Another 14,000 acres (5,700 ha) were seeded with the intent of being aerially straw mulched afterward. Because the aerial straw mulch contract was terminated prior to completion, approximately 7,800 acres (3,200 ha) were aerial seeded without any other treatment.*
- *"Colorado Cares Day" scarification, seeding and mulching* (fig. 13), for 125 acres (50 ha). On "Colorado Cares Day" (August 8, 2002) a variety of treatments were installed to utilize the services of 1,000 volunteers. These treatments included scari-

Figure 13—Volunteers using hand rakes and whirlybird seed spreaders to scarify and seed severely burned soils during the *Colorado Cares* event.

fication with McLeods, seeding with whirly-bird spreaders, and hand mulching.

- *Spot treatment of at-risk heritage sites.* Two heritage sites are at risk from high runoff flows and erosion. Strategically placed straw bales with rebar anchoring were placed to divert anticipated flood flows away from the sites.
- *Noxious weed spot-treatment and biologic control*, for 370 acres (1,500 ha). Herbicide spot treatments were applied to known weed infestations. Targeted sites posed a threat for the establishment, seed set and expansion into vulnerable fire areas and into uninfested areas directly outside of the burn. All treatments complied with the Pike and San Isabel National Forest Noxious Weed Environmental Assessment application guidelines.
- *Treatments on burned National Forest lands located above private land.* There is a considerable amount of private land within the Hayman Fire area (fig. 5). In many locations, moderate or high severity burned National Forest property is directly upslope of private homes. Six sites were treated with sandbag berm deflectors and directional felling in addition to the land treatments that occurred farther upslope.
- *Flood warning signs / system*. Three Remote Automated Weather Stations (RAWS) were installed to assist the National Weather Service in flood forecasting. In addition, 25 "Flash Flood Warning" signs were installed at key locations throughout the fire area, primarily at ingress points into the burn area.
- *Non-National Forest Land Treatments.* The BAER Team recommended no channel treatments. However, the Denver Water Board (DWB) installed straw bale check dams in tributaries above Cheesman Reservoir (fig. 14), a 25 by 100 foot (7.6 by 30 m) sediment basin on Goose Creek, and placed log sediment traps in other major gulches and drainages. The DWB also applied a polyacrylamide (PAM) as a soil binding agent on nearly 900 acres (360 ha).

Road and Trail Treatments –

- *Road maintenance,* for120 miles (190 km). In anticipation of flood flows from the burn area, road maintenance was implemented to ensure safe travel and reduce sediment sources. This included culvert and ditch cleaning, road grading, installation of rolling dips and armored grade dips, placement of rip rap and concrete barriers to protect road edges, and installation of silt lag dams and trash racks in drainages threatening road stability. Storm patrols will drive forest roads during or immediately following storm events to check culvert plugging or other drainage problems and thereby direct future road maintenance efforts.
- *Road closures*. Temporary road closures were necessary due to safety concerns (hazard trees, boulders rolling from steep burned slopes, and aerial rehabilitation treatment applications), possible road washouts and flash floods, and to aid in the rehabilitation of burned lands by simply reducing use. Closure methods included gates, large waterbars, boulders, and signs. Portable barricades will be used for rapid closure of open roads when warranted due to storms and flooding.

Effectiveness of Postfire Rehabilitation Treatments

The effectiveness of postfire rehabilitation treatments was recently reviewed by Robichaud and others (2000). Many of the different hillslope, channel, and road treatments recommended by Burned Area Emergency Rehabilitation (BAER) teams have not been extensively studied; however, some qualitative monitoring has occurred on various treatments. Overall, relatively little information has been published on most postfire emergency rehabilitation treatments (MacDonald 1988; Robichaud and others 2000).

Hillslope Treatments

Hillslope treatments such as mulches, contour-felled logs, and seeding are intended to reduce surface runoff and keep soil in place. These treatments are regarded

Figure 14—Straw bale check dams on Denver Water Board property within the Hayman Fire area.

as a first line of defense against postfire erosion and unwanted sediment deposition. However, the effectiveness of any hillslope rehabilitation treatment depend on the actual rainfall amounts and intensities—especially in the first years after the fire. Recent effectiveness monitoring on the Bobcat Fire in the northern Colorado Front Range showed that dry mulch, seeding, and contour log erosion barriers did not significantly reduce sediment yields in the first summer after the fire. This lack of effectiveness can be attributed to the intense rain event that overwhelmed all the treatment efforts. Some treatments did reduce sediment yields in the second year after burning, when rainfall was spread over several smaller events (Wagenbrenner 2003).

Mulch—Mulch is used to cover soil, thereby reducing rain impact, overland flow, and soil erosion. It is often used in conjunction with grass seeding to provide ground cover in critical areas. Mulch protects the soil from rainsplash, increases infiltration, and improves soil moisture retention thereby benefiting seeded grasses. Straw mulch has been shown to reduce erosion rates after wildfires by 50 to 94 percent (Bautista and others 1996; Faust 1998; Dean 2001; Wagenbrenner 2003).

Straw mulch was shown to be effective in a comparative study done for two monsoon seasons after the 2000 Cerro Grande Fire on the Bandolier National Monument and the Santa Fe National Forest in New Mexico (Dean 2001). Sediment from hillslope plots was compared using silt fence sediment traps (after Robichaud and Brown 2002). Although precipitation during the 2 study years was below normal, the plots treated with aerial seed and straw mulch yielded 70 percent less sediment than the no-treatment plots in the first year and 95 percent less in the second year. Ground cover transects showed that aerial seeding without added straw mulch provided no appreciable increase in ground cover relative to untreated plots. (Dean 2001). In the second year after the Bobcat Fire, Wagenbrenner (2003) reported sediment yields from mulched hillslope sites were significantly less than the sediment yields from untreated slopes and the slopes that were seeded without mulch.

Mulch is generally believed to be most effective on gentle and moderate slopes and in areas where high winds are not likely to occur. Wind either blows the mulch offsite or piles it so deeply that seed germination is inhibited. On steeper slopes, overland flow is more likely to wash the mulch downslope (Wagenbrenner 2003). Punching it into the soil, use of a tackifier or felling small trees across the mulch may increase on-site retention. The postfire dry mulching that was done after the Hayman Fire occurred on slopes ranging from 20 to 60 percent. With the exception of ridge tops, wind is not expected to be a significant issue; however, there is some chance that high intensity rain events might move some of this mulch downslope.

Mulch is frequently applied to improve the germination of seeded grasses. In the past, seed germination from grain or hay mulch was regarded as a bonus because this added cover to the site; however, the use of straw from pasture may introduce nonnative seed species that can persist and compete with the reestablishment of native vegetation. National Forests now seek "weed-free" mulch such as rice or wheat straw, but this is not always available in the locations and quantities needed. This problem was encountered during the rehabilitation efforts on the Hayman Fire. Although certified "weed-free" straw was used on the Hayman, cheat grass (*Bromus tectorium*) seed was found in some of the straw brought in for use in rehabilitation treatments. Straw and hay products may contain cheat grass and still meet Colorado weed-free standards. In addition to the introduction of nonnative species, there is concern that thick mulch may inhibit native herb and shrub germination. Shrub seedlings were found to be more abundant at the edge of mulch piles, where the material was less than 1 inch (2.5 cm) deep (Robichaud and others 2000).

Due to the cost and logistics of mulching, it is usually used when there are high downstream risks, such as above or below roads, above streams, or below ridge tops. Although mulch can be transported and distributed by helicopter, it is applied most easily where road access is available because bales must be trucked in. The use of helicopters to spread mulch is relatively new in postfire emergency rehabilitation and these were used to apply mulch on 7,700 acres (3,100 ha) after the Hayman Fire (table 7). Preliminary ground cover estimates on these areas showed approximately 70 percent ground cover immediately after application. The mulch thickness was not measured, but qualitative observations indicated that the straw bales broke apart as they fell from the cargo net and spread farther upon impact, resulting in a fairly even distribution of straw mulch over the ground surface.

Hydromulch—There are numerous fiber mulches, soil stabilizers, or combinations of material (tackifier, polymers, seeds, and so forth) that, when mixed with water and applied to the soil surface, form a matrix that help reduce erosion and foster plant growth. Hydromulch is most commonly applied on road cut and fill slopes, construction sites, and other disturbed areas with truck-mounted equipment. Several State transportation departments have tested the effectiveness of various hydromulch products on road cuts and fills. For unburned soils, an application of 3,500 lb per acre (3.9 Mg per ha) of hydromulch reduced erosion by 97 percent compared to bare soil under laboratory rainfall simulators (SDSU 2002).

The hydromulches applied after the Hayman Fire consisted of wood fibers, tackifers, soil binders, viscosity stabilizers, and water. Truck-mounted sprayers applied hydromulch on 1,500 acres (600 ha) along existing forest roads. Due to limitations in the spray equipment, treatment was limited to 200 feet (60 m) on either side of the road. When applied by helicopter, hydromulching is an expensive rehabilitation treatment. After the Hayman Fire, 1,500 acres (600 ha) of aerial hydromulching was applied to steep, inaccessible areas that drain directly to the South Platte River. Although the effectiveness of this treatment is expected to be high, there are no postfire effectiveness data available at this time.

Scarification—Scarification is a mechanical soil treatment aimed at improving infiltration rates in water repellent soils. Scarification may physically break up the water repellent layer, increase the macroporosity of the surface soil, and add roughness, thus increasing the infiltration rate. Hand rakes (McLeods) are commonly used in inaccessible, moderate slope terrain, whereas all-terrain vehicles (ATV) and tractors pulling harrows have been used on gentle slopes to break up the water repellent soil layers. The scarification depths using hand tools are generally 0.5 to 1.5 inch (1.3 to 3.8 cm) whereas machine pulled harrows or rippers can be 1 to 12 inches (2.5 to 30 cm) deep. Water repellent layers may be shallow (0.5 inch, 1.3 cm) and/or deep (6 inch, 15 cm). Therefore, for this treatment to be effective the depth of the water repellent layer must first be evaluated so that proper equipment can be used to break up that layer.

Scarification has been viewed as an effective treatment for roads, firebreaks, and trails, but less effective on hillslopes (Robichaud and others 2000). In the BAER team evaluation of the Hayman Fire, shallow water repellent conditions were observed. Thus, hand rakes and ATV pulled chain harrows (4 inch, 10 cm long harrow teeth) were used to scarify approximately 13,200 acres (5,300 ha).

Seeding—Historically, the most common BAER practice has been broadcast seeding of grasses, usually from aircraft. In the Hayman Fire 25,000 acres (10,100 ha) of National Forest land received aerial or hand seeding. Approximately 60 percent of the seeded acreage was also treated with mulch or scarification. The DWB aerial seeded 7,000 acres (2,800 ha) of their lands. Rapid vegetation establishment has been regarded as the most cost-effective method to promote water infiltration and reduce hillslope erosion (Miles and others 1989; Noble 1965; Rice and others 1965). Much of the research has focused on the effects of seeding on vegetative cover and the regeneration of native species rather than on infiltration and erosion. The studies reviewed by Robichaud and others (2000) used a wide variety of grass species, seed mixes, and application rates, and the data suggest that seeding does not assure higher plant cover during the critical first year after burning. Better cover and thereby better erosion control can be expected in the second and subsequent years. After the Bobcat Fire in the Colorado Front Range, Wagenbrenner (2003) found that seeding had no significant effect on sediment yields at the hillslope scale in either the first or second years. In addition, seeding had no significant effect on percent of vegetative cover compared to untreated areas (Wagenbrenner 2003).

Contour-Felled Logs—This treatment involves felling logs on burned-over hillsides and laying them on the ground along the slope contour. The contour-felled logs are intended to provide a mechanical barrier to overland flow, promote infiltration, and thereby reduce sediment movement. These barriers can also trap sediment, although this is not their primary intent. The logs need to be staked in place and the gaps between the logs and soil surface filled to prevent underflow (Robichaud and others 2000). Some recent installations have included the construction of soil berms at the end of the logs to increase their storage capacities. Although contour-felled logs had limited use on National Forest lands for the Hayman Fire rehabilitation, they were installed extensively on private lands within the burned area.

Dean (2001) found that plots treated with contour-felled logs as well as aerial seed and straw mulch yielded 77 percent less sediment in the first year and 96 percent in the second year; however, these results were not significantly different from the straw mulch with seed treatment alone. Recent postfire rehabilitation monitoring efforts for six paired watersheds have indicated that contour-felled logs can be effective for low to moderate rainfall intensity storm events. However, during high intensity rainfall events their effectiveness is greatly reduced. The effectiveness of contour-felled logs decreases over time. Once the sediment storage area behind the log is filled the barrier can no longer trap sediment that is moving downslope (Robichaud 2000; Wagenbrenner 2003).

Polyacrylamide (PAM)—PAM is a synthetic polymer that aids in aggregation of fine soil particles, which can reduce the erosion induced by flowing water. During the past few decades PAM has been used to reduce erosion in low-flow irrigation ditches, settle heavy metals in mine reclamation efforts, and increase sludge density in water treatment plants. More recently, PAM products have been introduced to hydraulic mulch/seed mixes to help bind soil particles. These products have been used on road cuts and fills and disturbed areas to stabilize soils and reduce erosion prior to revegetation.

The effectiveness of PAM for treatment of burned areas has not been tested. A single test using simulated rainfall on a severely burned plot in the northern Colorado Front Range found that sediment production from a plot treated with PAM initially had a much lower sediment yield than an untreated plot. However, sediment yield from the plot treated with PAM began to progressively increase after about 30 minutes, while the sediment yields from the untreated plot remained relatively constant until the end of the simulated rainfall (MacDonald, personal communication 2003). Although these preliminary results suggest some initial erosion-reduction benefit, the high variability in soil conditions in burned areas means that there may not be simple answers to the usefulness and potential effectiveness of PAM applications.

Channel Treatments

Channel treatments are designed for use in ephemeral or small-order channels to prevent or reduce flooding and debris torrents further downstream. Some in-channel structures slow water flow and allow sediment to settle out; the sediment is released gradually as the structure decays. Much less information is available on channel treatments after wildfire than on hillslope treatments (Robichaud and others 2000).

Straw Bale Check Dams—The DWB used 29,000 straw bales construct check dams in the swales and small tributaries that drain directly into Cheesman Reservoir. These structures were not used on National Forest lands; however, they have been installed and evaluated after other fires. These studies indicate that straw bale check dams are effective if they do not fail (Miles and others 1989; Fites-Kaufman 1993; Collins and Johnston 1995; Niehoff 1995). Failures due to blowouts, piping between bales, or undercutting were commonly reported. Blowouts are particularly common for straw bale check dams put into deeply incised or steeply sloped streams and after large storm events. High postfire erosion means sediment can quickly fill the area behind straw bale check dams, making them ineffective and susceptible to failure.

Goldman and others (1986) found that straw bales usually last less than 3 months and recommended that they only be used when flows are less than 11 cfs (0.3 $m^3 s^{-1}$). The bales also should be removed when the accumulated sediment exceeds one-half of the check dam height. More damage can result from failed barriers than if no barrier were installed (Goldman and others 1986). Denver Water Board maintenance of their straw bale check dams in the Hayman Fire area has included the use of small equipment to clean out accumulated sediment after storms and some reinforcement and extension of compromised structures.

Road Treatments

Generally, forest road structures are not directly damaged by fire but the consequences of fire (increased peak flows, movements of material downslope, sedimentation, etc.) can dramatically affect roads. Since it is impossible to design and build all stream crossings to withstand extreme storm flows, Best and others (1995) recommended increasing crossing capacity to minimize the consequences of culvert exceedence as the best approach for forest road stream crossings. Consequently, BAER road treatments include practices aimed at increasing the capabilities of roads and road structures to handle larger amounts of runoff and sediment (Robichaud and others 2000). The road treatments recommended by the Hayman Fire BAER team included outsloping, ditch and culvert cleaning, armored stream crossings, and rolling dips as well as riprap and concrete barriers for road edge protection. Trash racks and storm patrols try to prevent culverts from becoming blocked with organic debris, which could result in road failure that would increase downstream flood or sediment damage. Comprehensive discussions of road-related treatments and their effectiveness can be found in Packer and Christensen (1977), Goldman and others (1986), Burroughs and King (1989), and Copstead (1997).

Monitoring Postfire Rehabilitation Treatments

Monitoring the effectiveness of postfire rehabilitation treatments is important to determine if the treatments are functioning as desired and to compare the benefits of various treatments. Monitoring also is essential in determining the conditions under which different treatments are effective and thereby the limitations of each treatment. Both implementation and effectiveness monitoring need to occur. This section outlines a process for monitoring postfire rehabilitation as well as postfire rehabilitation monitoring efforts on the Hayman Fire.

Implementation Monitoring

Implementation monitoring ensures that postfire rehabilitation treatments are installed as designed for maximum effectiveness. To be effective, implementation monitoring has to be conducted as the individual actions are being completed. Close ties between the installation activity and the monitoring are critical for two reasons: (1) problems can be addressed while the fire crews, contractors, and other personnel are still on site; and (2) design problems may be readily identified, and modifications made in order to adjust the treatments being applied elsewhere. In the case of dry mulching, project inspectors check the application rate and coverage area as well as ensuring that straw quality, seed content, and preparation specifications are met.

During the installation of postfire rehabilitation treatments, logistical difficulties are usually encountered and these frequently require revisions to the recommended treatments. The preceding section described some of the adjustments made on the Hayman Fire during the implementation process. For example, the acreage to be treated by aerial hydromulch (with seed) was reduced and replaced by aerial dry mulch (with seed) treatment. Subsequently the acreage to be treated with aerial dry mulch was reduced and replaced by aerial seeding alone (no mulching or scarification). Changes in treatment implementation plans are common. Documentation and explanation of these changes may be useful for future rehabilitation efforts.

Effectiveness Monitoring

A major limitation to the design of postfire rehabilitation treatments is the lack of information on their effectiveness (Robichaud and others 2000). The paucity of data on the effectiveness of different BAER treatments means that funds are being spent with little surety of the potential benefits. As wildfires will continue to occur, there will be a continuing need to minimize postfire erosion rates and protect downstream resources, BAER treatments are almost certain to be applied after future wildfires. Hence, effectiveness monitoring must be conducted on current and future fires, as this information is necessary to determine: (1) the relative effectiveness of the different BAER treatments to achieve specified objectives, such as reduction in postfire runoff and erosion rates; (2) the change in treatment effectiveness over time; (3) the variation in treatment effectiveness over a range of storm events; (4) the relative treatment effectiveness for different watershed conditions, such as topography, geology, soils, vegetation, and so forth; and (5) an estimated cost-benefit analysis for the different treatments. Quantitative data from these monitoring efforts will not only guide future responses to postfire rehabilitation but also can be used to build and refine predictive models.

Robichaud and others (2000) examined 157 postfire monitoring reports generated between 1967 and 1998. They found that these monitoring reports varied widely in content. Only 55 of 157 (35 percent) reports contained quantitative data. The other 65 percent contained qualitative assessment of treatment success, such as trip reports or photos. The variation in the type of assessment made it difficult to tabulate and compare the results from different postfire rehabilitation efforts.

If effectiveness monitoring were required whenever significant BAER treatments were installed, the resulting data would facilitate comparisons between treatments and an assessment of the factors and conditions that limit treatment effectiveness. The large spatial and temporal variability in postfire runoff and erosion processes implies that effectiveness monitoring has to be replicated within and between areas. The collection of such data would provide better guidance for future management decisions, and allow a more rigorous assessment of the benefits that might be obtained from a given treatment. Recent changes in Federal land management agency policies allow up to 10 percent of BAER funds to be used for monitoring, so there is no fundamental reason why implementation and effectiveness monitoring should not be conducted after any wildfire that receives BAER treatments.

Monitoring as Part of the BAER Team Report—An important step for improving postfire rehabilitation treatment monitoring is to include implementation monitoring and the general outline for an effectiveness monitoring program as a required component of all BAER reports that recommend rehabilitation treatments. Given the time and logistical constraints on the BAER team, they cannot be expected to develop the details of a monitoring program. However, the monitoring section can outline the primary monitoring goals, how these goals might be achieved, provide an estimated budget, and indicate whether the monitoring can be conducted in-house or should be contracted out.

Generally, the design of an effectiveness monitoring program requires individuals with some knowledge of statistics and field measurement techniques. If expertise is not available locally, it may be advantageous to contact Forest Service researchers, universities, or similar agencies. An approximate budget is needed so that funds can be immediately made available for monitoring, as the installation of monitoring sites should occur simultaneously with the installation of the BAER treatments. The development of partnerships on a case-by-case basis means that flexibility is needed in how monitoring dollars provided through the BAER process can be spent.

Effectiveness monitoring needs to be done as quickly as possible, as the first storms typically pose the greatest risk to downstream resources, and we have few data on the immediate effectiveness of BAER treatments. In addition, effectiveness monitoring requires quantifiable data collection and a multiyear commitment (for example monitoring protocol, see Robichaud and Brown 2002). For monitoring projects to be successful, timely data collection, analyses, and reporting are needed (MacDonald 1994).

Untreated Areas Needed for Comparison—To evaluate the effectiveness of postfire rehabilitation treatment(s), untreated areas must be available for comparison. Burned but untreated areas provide a control, or baseline, from which effectiveness can be measured. These areas can be used to assess both short- and long-term effectiveness of treatments as well as ecosystem response to the fire. The untreated areas must be comparable to areas designated for treatment. A small number of untreated areas can serve as the controls for a much larger number of different treatments, as long as the controls have a similar mean and range of conditions as the various treated areas.

Open Monitoring Program—The monitoring program must be transparent and the results reported at regular intervals. Much of the controversy over postfire treatments is due to the lack of hard data on the effectiveness of different treatments. The development and regular reporting of results from monitoring programs are needed to guide future management actions. Regular reports of monitoring data will show that the Forest Service and other management agencies are actively evaluating the effects of their actions. An open and transparent presentation of the monitoring results also allows concerned agencies and individuals to make their own judgments based on data. By collecting and reporting monitoring data, the current debate over land management actions will be placed on a more objective basis, and this has the potential to reduce the stridency of this debate.

Current Monitoring in the Hayman Fire Area—As previously discussed, the Forest Service actively monitored the implementation of rehabilitation treatments after the Hayman Fire. Daily briefings allowed for immediate response to circumstances encountered during installation of the treatments. For example, the locations of some treatment polygons were changed when, upon inspection, burn severity was found to be less than indicated by the burn severity map. In addition, daily decisions were required to effectively deploy the materials, equipment, and labor required to install the different rehabilitation treatments. Implementation monitoring by seven to 10 project inspectors occurred while the treatment contractors were working onsite and lasted approximately 60 days.

Immediately after fire suppression activities ended, hillslope treatment effectiveness monitoring was being established by Robichaud (USDA Forest Service, Rocky Mountain Research Station, Moscow, ID) and MacDonald (Colorado State University, Fort Collins, CO). The BAER team has decided that the effectiveness monitoring data from these sites would meet the needs established by the current BAER program and will support these efforts rather than developing an independent program. In addition, the location and size of burned but untreated "exclusion" areas (300 acres, 120 ha) were established during the reconnaissance of the effectiveness monitoring sites (fig. 5).

Robichaud (unpublished study plan 2002) established six small watershed monitoring sites (10 acres, 4 ha) within high burn severity areas of the Hayman Fire Area. Four of the six small watersheds have been or will be treated with (1) aerial hydromulching, (2) aerial dry mulch, (3) contour-felled logs, and (4) salvaged logged. Salvage logging is not a postfire rehabilitation treatment, but it is included in this monitoring effort to evaluate its effect on runoff and erosion. Two of the sites have been left untreated as controls. Each site has a sediment trap and weir constructed at the outlet of the watershed. A complete weather station and four tipping bucket rain gauges are also installed onsite. After each storm event, the sediment will be collected, measured, and analyzed so that the treated and nontreated watersheds can be compared. These sites will be monitored for 5 years. In addition, 32 rill study plots (300 ft^2, 27 m^2) with silt fence sediment traps (Robichaud and Brown 2002) have been established to compare treatments. Eight plots of each treatment—straw mulch, wood straw mulch (new product), hand scarification, and untreated controls—are in place and being monitored.

MacDonald (unpublished study plan 2002) is also monitoring sites within the Hayman Fire area. At the watershed scale, 2.5 foot (0.75 m) H-flumes have been established in Saloon Gulch (840 acres, 340 ha) and Brush Creek (1,500 acres, 620 ha) where pre- and postfire data have been collected. At the hillslope scale, 20 paired swales (one control and one treated) have been established in Upper Saloon gulch and the adjacent Schoonover Fire. Swales range from 0.1 to 2.5 acres (0.06 to 1 ha) in size and have silt fence sediment traps. Three to six pairs of swales are being used to evaluate the following treatments: (1) ground-based dry mulch, (2) ground-based hydromulching, (3) hand scarification with seeding, and (4) wet PAM application. Four other swales in Upper Saloon gulch are being used to monitor sediment production rates from areas treated by aerial hydromulch. The sediment in each swale is being regularly collected, measured, and analyzed. Six tipping bucket rain gauges have been installed, and sediment production rates will be related to storm magnitudes and intensities.

The Pike-San Isabel National Forest South Platte Ranger District has begun sampling suspended sediment and nutrients in seven drainages within the Hayman Fire area. The USGS has also begun sampling nutrients, metals, dissolved organic carbon (DOC), and suspended sediment on Fourmile Creek, which drains a burned watershed, and Pine Creek, which drains an unburned watershed adjacent to the Hayman Fire area. Sampling for both studies will be done on a monthly basis and during some storm events from April through November 2003. These drainages have mixed burn severities and some have been treated with a variety of treatments. The main objective of these studies is to compare water quality parameters between drainages (Entwistle, personal communication 2003; Martin, personal communication 2003).

Key Information Needs

Emergency watershed rehabilitation efforts are designed to protect resources at risk while minimizing expenditures on measures that may be ineffective or adversely impact burned watersheds. Deficiencies in the information available to the Hayman BAER team have been identified. In most cases these deficiencies apply to other burned areas as well as the Hayman Fire and include:

- Knowledge of return intervals for short-duration, high-intensity thunderstorms and how storm magnitudes vary with increasing aerial extent.
- The relation between rainfall, runoff, and erosion from the burned area. This is needed for accurate predictions of downstream flooding and sedimentation, and indications of how this relation may change over time.
- Burn severity maps that accurately depict fire effects on soil properties such as erodibility and soil water repellency.
- Knowledge of the effectiveness of BAER treatments for given storm types, ecosystems, and geographic locations.

Summary

Burned watersheds respond to rainfall faster than unburned watersheds. Although flash flooding, erosion, and the mobilization of large amounts of bedload and suspended sediments are commonly observed and have been documented in the literature, we have limited knowledge and ability to predict this response, especially for short-duration high-intensity storms. We also have little data on the effectiveness rehabilitation treatments to reduce runoff and erosion rates. This is particularly true for the newer treatments used on the Hayman Fire area such as hydromulch, aerial dry mulch, and scarification. Active monitoring projects have been established in the Hayman Fire area; however, treatment effectiveness results will not be available for several years. Monitoring needs to be an integral part of the postfire emergency rehabilitation treatment process and maintained until recovery approaches prefire conditions for the parameters of interest.

Acknowledgments

The authors thank Greg Bevenger (Shoshone National Forest), Steve Johnson (Kootenai National Forest), Ken Kanaan (Pike and San Isabel National Forest), and Pete Wohlgemuth (Pacific Southwest Research Station) for their careful review and significant contributions to this chapter.

References

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, DC. 493 p.

Arkell, R. E.; Richards, F. 1986. Short duration rainfall relations for the Western United States, Conference on climate and water management—a critical era and conference on the human consequences of 1985’s climate. 1986 August 4-7; Asheville, NC.

Bailey, Reed W.; Copeland, Otis L. 1961. Vegetation and engineering structures in flood and erosion control. In: Proceedings, 13th Congress, 1961 Sept.; Vienna, Austria. International Union of Forest Research Organization Paper 11-1. 23 p.

Bautista, S.; Bellot, J.; Vallejo, V. R. 1996. Mulching treatment for postfire soil conservation in a semiarid ecosystem. Arid Soil Research and Rehabilitation 10: 235-242.

Benavides-Solorio, J. D.; MacDonald, L. H. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. In: Anderson, M.G.; Peters, N.E.; Walling, D. (eds) Hydrological Processes 15 (15): 2931-2952.

Benavides-Solorio, J. D. 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Fort Collins, CO: Colorado State University. 218 p. Thesis.

Best, D. W.; Kelsey, D. K.; Hagans, D. K.; Alpert, M. 1995. Role of fluvial hillslope erosion and road construction in the sediment budget of Garret Creek, Humboldt County, California. In: Nolan, K. M.; Kelsey, H. M.; Marron, D. C. (eds.) Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. Professional Paper 1454. Washington, DC: U.S. Geological Survey: M1-M9.

Bolin, S. B.; Ward, T. J. 1987. Recovery of a New Mexico drainage basin from a forest fire. In: Swanson, R. H.; Bernier, P. Y.; Woodard, P. D., ed., Proceedings: Vancouver symposium; 1987 August; Vancouver, British Columbia, Canada; Forest Hydrology and Watershed Management, IAHS; 167: 191-198.

Burroughs, Jr., Edward R.; King, John G. 1989. Reduction in soil erosion of forest roads. Gen. Tech. Rep. INT-264. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 21 p.

Campbell, R. E.; Baker, M. B., Jr.; Ffolliott, P. F. 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. Res. Pap. RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 12 p.

Collins, L. M.; Johnston, C. E. 1995. Effectiveness of straw bale dams for erosion control in the Oakland Hills following the fire of 1991. In: J.E. Keeley and T. Scott (eds.). Brushfires in California wildlands: ecology and resource management. Fairfield, WA: International Association of Wildland Fire: 171-183.

Colorado Water Quality Control Division (WQCD). 2002. Total maximum daily load assessment upper South Platte River, segment 1A, sediment. Douglas, Jefferson, Park and Teller counties, CO. Report on file. Denver, CO: Department of Public Health and Enviornment. 28 p.

Copstead, R. 1997. The water/road interaction technology series: an introduction. No.9777 1805-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology Center. 4 p.

Dean, A. E. 2001. Evaluating effectiveness of watershed conservation treatments applied after the Cerro Grande Fire, Los Alamos, New Mexico. M.S. Thesis. University of Arizona: Tucson, AZ: 116 p.

DeBano, L. F.; Ffolliott, P. F.; Baker, M. B. Jr. 1996. Fire severity effects on water resources. In: Ffolliott, P. F.; DeBano, L. F.; Baker, M. B. Jr.; Gottfried, G. J.; Solis-Garza, G.; Edminster,C. B.; Neary, D. G.; Allen, L. S.; Hamre, R. H. (tech. coords.). Effects of fire on Madrean province ecosystems - A symposium proceedings. Gen. Tech. Rep. RM-289. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 77-84.

DeBano, L. F.; Neary, D. G.; Ffolliott, P. F. 1998. Fires's effects on ecosystems. New York: John Wiley & Sons. 333 p.

Elliot, W. J.; Hall, D. E.; Graves, S. R. 2001. Forest Service WEPP Forest Service interfaces for the Water Erosion Prediction Project computer model, Moscow, ID: U.S. Department of Agriculture, Forest Service, [Online]. Available: http://forest.moscowfsl.wsu.edu/fswepp/ [2002, July]

Entwistle, D. C. 2003. [Personal communication]. April 30. Morrison, CO: Pike-San Isabel National Forest and Cimarron Comanche National Grasslands, South Platte Ranger District, USDA Forest Service.

Farmer, Eugene E.; Fletcher, Joel E. 1972. Some intra-storm characteristics of high-intensity rainfall burst. In: Distribution of Precipitation in Mountainous areas, Geilo Symposium, Norway; 1972 July 31-August 5; Geneva, Switzerland: World Meteorological Organization; 2: 525-531.

Faust, Robert. 1998. Lesson plan: Fork fire soil loss validation monitoring. Unit VIII, Long term recovery and monitoring. In: Burned area emergency rehabilitation (BAER) techniques, 1998. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. (course notebook).

Fites-Kaufman, Russell.1993. Survey of check dams in the Cleveland Fire Area. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Eldorado National Forest, CA. 3 p.

Goldman, S. J.; Jackson, K.; Bursztynsky, T. A. 1986. Erosion and sediment control handbook. San Francisco, CA: McGraw-Hill. 360 p.

Hawkins, R. H.; Greenberg, R. J. 1990. Wildcat4 Flow Model. [This edition further enhances Moore's version] School of Renewable Natural Resources, University of Arizona, Tucson, AZ. BLM contact: Dan Muller, Denver, CO. Kozlowski, T. T.; Ahlgren, C. E. eds.1974. Fire and ecosystems. New York: Academic Press. 542 p.

Hendricks, B. A.; Johnson, J. M. 1944. Effects of fire on steep mountain slopes in central Arizona. Journal of Forestry. 42: 568-571.

Hungerford, R. D. 1996. Soils- fire in ecosystem management notes: unit II-I. Marana, AZ: U.S. Department of Agriculture, Forest Service, National Advanced Resource Technology Center.

John, T. J. 2002. Soil report for Hayman Fire Burned Area. Prepared for: U.S. Department of Agriculture, Forest Service, 2002. Hayman Fire—burned area report. (Hayman Fire 2500-8, original 7/5/02, revised 8/21/02) Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Pike and San Isabel National Forest, Pueblo, CO. 9 p.

Kozlowski, T. T.; Ahlgren, C. E., eds.1974. Fire and ecosystems. New York: Academic Press. 542 p.

Kunze, M. D. 2003. Streamflow and sediment yield following the 2000 Bobcat Fire, Colorado Front Range, Fort Collins, CO: Colorado State University. 81 p. Thesis.

Kuyumjian, G. A.; Meador, K. L.; Higginson, B.; Brobst, R. B.; Entwistle, D. C. 2002. Hayman Fire PSICC June 2002 hydrology report. Prepared for: U.S. Department of Agriculture, Forest Service, 2002. Hayman Fire—burned area report. (Hayman Fire 2500-8, original 7/5/02, revised 8/21/02) Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Pike and San Isabel National Forest, Pueblo, CO, 8 p.

MacDonald, L.H. 2003. [Personal communication]. October 20. Fort Collins, CO: Colorado State University, Department of Earth Resources.

MacDonald, L. H. 1994. Developing a monitoring project, Journal of Soil and Water Conservation, 4a(3): 221-227.

MacDonald, L. H. 1988. Rehabilitation and recovery following wildfires: a synthesis, Proceedings of symposium on fire and watershed management; 1988 October 26-28; Sacramento, CA. Gen. Tech. Rep. PSW-109. Berkley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station: 141-144.

Martin, D. A. 2003. [Personal communication]. April 30. Boulder, CO: US Geological Survey, Water Resources Division, National Research Program.

Megahan, Walter F.; Molitor, Delbert C. 1975. Erosion effects of wildfire and logging in Idaho. In: Watershed management symposium: 1975 August; Logan, UT: American Society of Civil Engineers Irrigation and Drainage Division: 423-444.

Miles, Scott R.; Haskins, Donald M.; Ranken, Darrel W. 1989. Emergency burn rehabilitation: cost, risk, and effectiveness. In: Berg, Neil H., technical coordinator. Proceedings of the symposium on fire and watershed management, 1988 October 26-28; Sacramento, CA. General Technical Report PSW-109. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station: 97-102.

Moody, J. A.; Martin, D. A. 2001a. Hydrologic and sedimentologic response of two burned watersheds in Colorado, U.S. Geological Survey Water Resources Investigation Report 01-4122, Denver, CO.

Moody, John A.; Moody, Deborah A. 2001b. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range, Earth Surface Processes and Landforms 26:1049-1070.

Morris, S. E.; Moses, T. A. 1987. Forest fire and the natural soil erosion regime in the Colorado front range, Annals of the Association of American Geographers, 77(2): 245-254.

Neary, D. G.; Gottfried, G. J. 2001. Post-wildfire peak flood flows: Causes and effects. In: Proceedings Society of American Foresters 2000 National Convention; 2000 November 16-20; Washington, DC, Society of American Foresters, Bethesda, MD: 459-463.

Neary, D. G.; Klopatek, C. C.; DeBano, F. F.; Ffolliott, P. F. 1999. Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management 122: 51-71.

Niehoff, Jerry. 1995. Mary-mix monitoring trip. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Idaho Panhandle National Forest, ID. 3 p.

Noble, Edward L. 1965. Sediment reduction through watershed rehabilitation. In: Proceedings of the federal inter-agency sedimentation conference 1963. Washington, DC: U.S. Department of Agriculture, Miscellaneous Publication 970: 114-123.

Noble, Edward L.; Lundeen, Lloyd. 1971. Analysis of rehabilitation treatment alternatives for sediment control. In: Symposium on forest land uses and stream environment, 1971 October 19-21; Corvallis, OR. Oregon State University, School of Forestry and Department of Fisheries and Wildlife, Continuing Education Publications: 86-96.

Packer, P. E.; Christensen, G. F. 1977. Guides for controlling sediment from secondary logging roads. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, and Missoula MT: U.S. Department of Agriculture, Forest Service, Northern Region. 42 p.

Rice, R. M.; Crouse, R. P.; Corbett, E. S. 1965. Emergency measures to control erosion after a fire on the San Dimas Experimental Forest. In: Proceedings of the federal inter-agency sedimentation conference 1963; Washington, DC: U.S. Department of Agriculture, Miscellaneous Publication 970:123-130.

Rich, L. R. 1962. Erosion and sediment movement following a wildfire in a ponderosa pine forest of central Arizona. Res. Note 76. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 12 p.

Rinne, J. N. 1996. Short-term effects of wildfire on fishes and aquatic macroinvertebrates in the southwestern United States. North American Journal of Fisheries Management 16: 653-658.

Robichaud, P. R. 2000. Fire and erosion: evaluating the effectiveness of a post-fire rehabilitation treatment, contoured-felled logs. Proceedings, Watershed management & operations management conference; 2000 June 20-24; Fort Collins, CO. Reston, VA: American Society of Civil Engineers, c2000.

Robichaud, P. R.; Beyers, J. L.; Neary, D. G. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech. Rep. RMRS-GTR-63. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p.

Robichaud, P. R.; Brown, R. E. 2000 (revised) [original publication, 1999]. What happened after the smoke cleared: onsite erosion rates after a wildfire in eastern Oregon. In: Olsen, D. S.; Potyondy, J. P. (eds.), Proceedings, Wildland Hydrology Conference, 1999 June; Bozeman, MT. Hernon,VA: American Water Resource Association: 419-426.

Robichaud, Pete R.; Brown, Robert E. 2002. Silt fences: An economical technique for measuring hillslope soil erosion. Gen. Tech. Rep. RMRS-GTR-94. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 24 p.

Ryan, K. C.; Noste, N. V., 1983. Evaluating prescribed fires. In: Lotan, J. E.; Kilgore, B. M.; Fischer, W. C.; Mutch, R. W., tech. coords. Proceedings, symposium and workshop on wilderness fire. Gen. Tech. Rep. INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 230-238.

San Diego State University. 2002. Results from a study of Canadian Forest Products Ltd. EcoAegis™: Runoff characteristics and sediment retention under simulated rainfall conditions. Prepared for: Canadian Forest Products Ltd; Project Reference No. 2001-02-CAN. San Diego, CA: San Diego State University/Soil Erosion Research Laboratory. 21 p.

U.S. Department of Agriculture, Forest Service, 2002. Hayman Fire—burned area report. (Hayman Fire 2500-8, original 7/5/02, revised 8/21/02) Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Pike and San Isabel National Forest, Pueblo, CO. 12 p.

Wagenbrenner, J. W. 2003. Effectiveness of burned area emergency rehabilitation treatments, Colorado Front Range. Fort Collins, CO: Colorado State University. 193 p. Thesis.