Hayman Fire Case Study Analysis:

Postfire Rehabilitation

Pete Robichaud, L. MacDonald, J. Freeouf, Dan Neary, D. Martin

Introduction

Our team has been asked to review and comment on immediate postfire effects. Specifically, we were asked to review the existing knowledge and science on changes in watershed responses and effectiveness of postfire rehabilitation treatments. We will review monitoring protocols and techniques related to erosion, water quality, and treatment effectiveness that are appropriate for burned areas. Additionally, we will identify appropriate untreated areas that should be established to allow meaningful comparison to natural recovery. Finally, we will identify knowledge gaps that need to be addressed to guide the selection of postfire rehabilitation treatments.

Our approach first builds on the current literature pertaining to postfire changes in watershed response and sedimentation. Then we describe the soils, hydrology, values at risk, and selection of treatment methods for the Hayman Fire area. This is followed by current knowledge of postfire rehabilitation treatment effectiveness with a focus on treatments that are being used on the Hayman Fire area. We continue with a discussion of monitoring protocols. We finish by delineating the shortfalls in our knowledge and the uncertainty we have in the effectiveness of the rehabilitation treatments currently being used.

Immediate Effects of Fire on Western Forest Watersheds

Although the general effects of fire on Western forested landscapes are well documented (Agee 1993; DeBano and others 1998; Kozlowski and Ahlgren 1974), the effects of postfire erosion and rehabilitation treatment effectiveness have not been studied extensively. The available literature does not cover the matrix of climate-geology-soil-vegetation complexes that occur in the Western United States. Postfire rehabilitation treatment effectiveness needs to be evaluated in an ecosystem context; consequently, the relevant scientific literature on postwildfire conditions is summarized from an ecosystem perspective.

Burn Severity

All disturbances produce impacts on ecosystems. The magnitude of these impacts depends on ecosystem resistance and resilience, as well as the severity of the disturbance. The variability in resource damage and response from site to site and ecosystem to ecosystem is highly dependent on burn severity.

Burn severity is a qualitative measure of the effects of fire on site resources (Hartford and Frandsen 1992; Ryan and Noste 1983). As a physical-chemical process, fire produces a spectrum of effects that depend on interactions of energy release (intensity), duration, fuel loading and combustion, vegetation type, climate, topography, soil, and area burned.

Fire intensity is an integral part of burn severity, and the terms are often incorrectly interchanged. Intensity refers to the rate at which a fire is producing thermal energy in the fuel-climate environment (DeBano and others 1998). Intensity is measured in terms of temperature and heat yield. Surface temperatures can range from 120 to greater than 2,700 °F (50 to greater than 1,500 °C). Heat yields per unit area can vary 60- to 70-fold with a fuel such as short, dead grass on the low end to heavy logging slash on the high end (Pyne and others 1996).

Duration is the component of burn severity that results in the most damage to soils and watersheds, and hence to ecosystem stability. Rate of spread is an index of fire duration and can vary from 1.6 ft per week (0.5 m per week) in smoldering peat fires to as much as 15 miles per hour (25 km per hour) in catastrophic wildfires. Fast moving fires in fine fuels, such as grass, may be intense in terms of energy release per unit area, but they do not transfer as much heat to the forest floor, mineral soil, or soil organisms as slow moving fires in moderate to heavy fuels (Campbell and others 1995).

Some aspects of burn severity can be quantified, but burn severity cannot be expressed as a single quantitative measure that relates to resource impact. Therefore, relative magnitudes of burn severity, expressed in terms of the postwildfire appearance of litter and soil (Ryan and Noste 1983), are used to place burn severity into broadly defined, discrete classes, ranging from low to high. A general burn severity classification developed by Hungerford (1996) relates burn severity to the soil resource response (table 1).

Fire Impacts on Watersheds

Soils, vegetation, and litter are critical to the functioning of hydrologic processes. Watersheds with good hydrologic conditions (greater than 75 percent of the ground covered with vegetation and litter), and adequate rainfall 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 accumulated forest floor material and vegetation, altering infiltration by exposing soils to raindrop impact or creating water repellent conditions (DeBano and others 1998). When severe fire produces hydrologic conditions that are poor (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 burn severity and in some moderate burn severity areas. Given that 35 percent of the Hayman Fire area is rated *high burn severity* and another 16 percent is rated *moderate burn severity*, it is likely that poor hydrological conditions exist in up to 45 percent of the burned area (fig. 1).

Within a watershed, sediment and water responses to wildfire are often a function of burn severity and the occurrence of hydrologic events. Even severely burned areas will have minimal soil loss in the absence of precipitation. However, when a major precipitation event follows a large, moderate- to high-burn severity fire, impacts can be far reaching. The burned area from the Hayman Fire will likely be impacted by soil loss from hillslopes, increased runoff, peakflows, and sediment delivery to streams.

Increases in annual water yield (runoff from a specified watershed) after wildfires and prescribed fires are highly variable (DeBano and others 1998; Robichaud and others 2000). The increase in runoff rates after wildfires can be attributed to several factors. In coniferous forests and certain other vegetation types, such as chaparral, the volatilization of organic compounds from the litter and soil can result in a water repellent layer at or near the soil surface (DeBano 2000). The net effect of this water repellent layer is to decrease infiltration, which causes a shift in runoff processes from subsurface lateral flow to overland flow (Campbell and others 1977; Inbar and others 1998). The loss of the forest litter layer can further reduce infiltration rates through rainsplash erosion and soil sealing (Inbar and others 1998; DeBano 2000). Loss of the protective litter layer and soil water repellency has occurred in the Hayman Fire area. These two factors combined will likely cause a large increase in runoff, which should diminish within 2 to 5 years as vegetation regrows.

Flood peakflows produce some of the most profound watershed and riparian impacts that forest managers have to consider. The effects of fire disturbance on storm peakflows are highly variable and complex. Intense short duration storms that are characterized by high rainfall intensity and low volume have been associated with high stream peakflows and significant erosion events after fires (DeBano and others 1998; Neary and others 1999; Moody and Martin 2001).

In the Intermountain West, high-intensity, short-duration rainfall is relatively common (Farmer and Fletcher 1972). Unusual rainfall intensities are often associated with increased peakflows from recently burned areas (Croft and Marston 1950). Moody and Martin (2001) measured rainfall intensities after the Buffalo Creek Fire in the Front Range of Colorado that was greater than 0.4 inches per hour (10 mm per hour). Even in short bursts of 15 to 30 minutes, rainfall of such intensity will likely exceed the average infiltration rates of many soils such that streamflow is domi-

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

	Burn severity		
Soil and litter parameter	**Low**	**Moderate**	**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,deeply charred
Ash color	Black	Light colored	Reddish, orange
Mineral soil	Not changed	Not changed	Altered structure,porosity, etc
Soil temp. at 0.4 inch (1 cm)	<120 °F(<50 °C)	210-390 °F(100-200 °C)	>480 °F(>250 °C)
Soil organism lethal temp.	To 0.4 inch (1 cm)	To 2 inches (5 cm)	To 6 inches (16 cm)

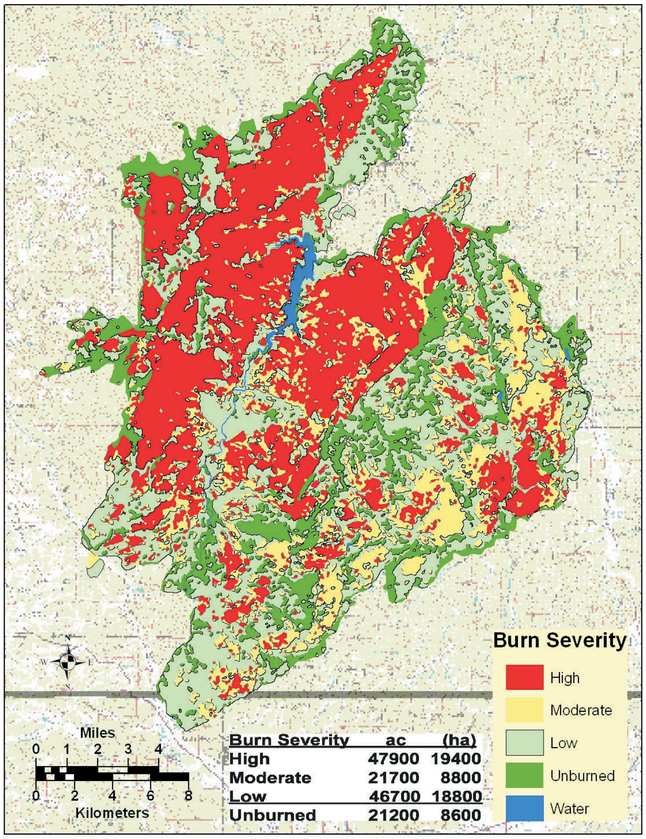

Figure 1—Burn severity map of the Hayman Fire area.

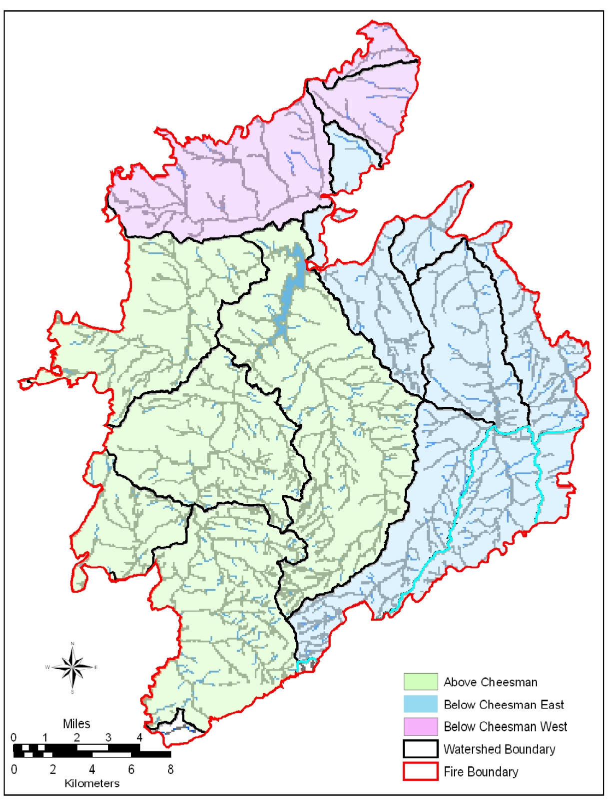

Figure 2—Sixth-level watershed map of the Hayman Fire area.

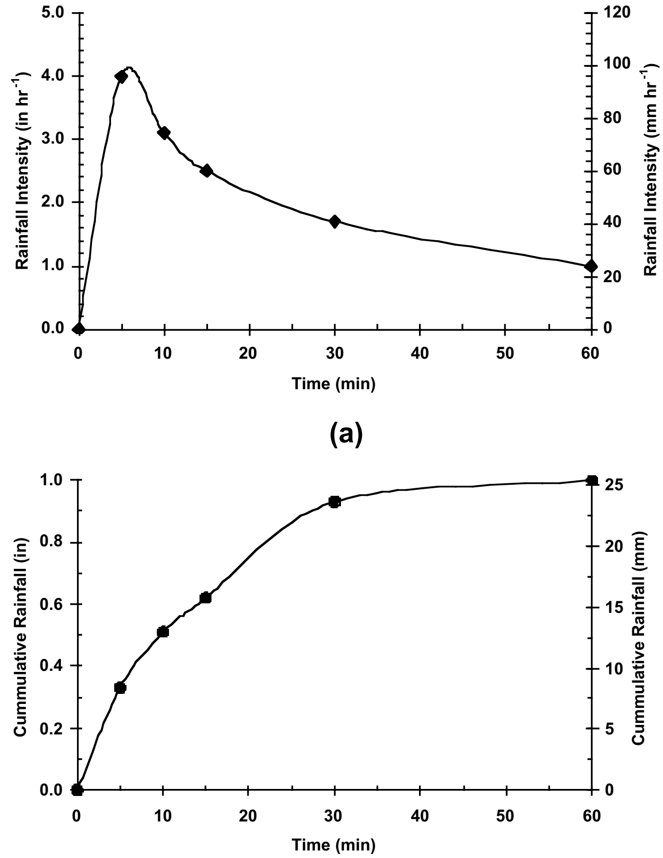

Figure 3—Distribution of Design Storm Precipitation over time.

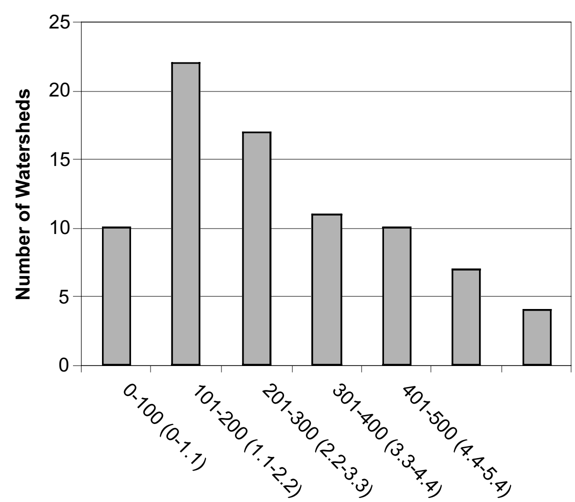

Figure 4—Watershed distribution in relation to predicted postfire runoff.

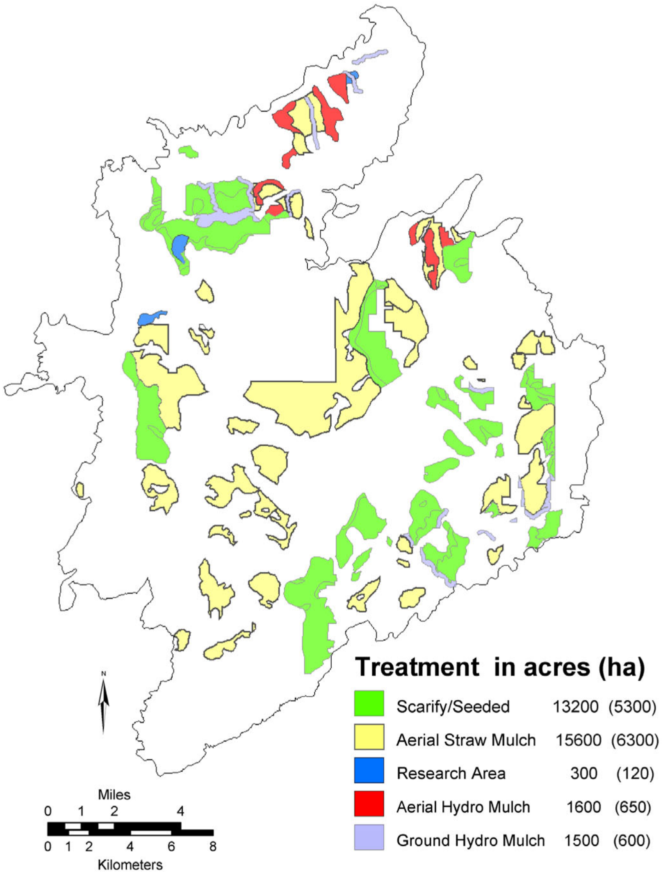

Figure 5—Postfire rehabilitation treatment map of the Hayman Fire area.

Figure 7—Hydromulch staging area.

Figure 8—Helicopter with tanks for hydromulch slurry.

Figure 6—Ground-based application of hydromulch with seed.

Figure 9—Aerial application of hydromulch with seed

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 all terrain vehicle.

Figure 13—Hand scarification with volunteers from *Colorado Cares* event.

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

nated by surface runoff that produces floods (Moody and Martine 2001). Water repellent soils and cover loss 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 areal extent but will produce profound localized flooding effects. 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). Although most flood peakflows are much less than this catastrophic upper figure, flood peak increases of even twice prefire conditions can produce substantial damage.

The concepts of stormflow timing are well understood within the context of wildland hydrology. However, definitive conclusions have been difficult to draw from some studies because of combined changes in volume, peak and timing at different locations in the watershed, and the severity and size of the disturbance in relation to the size of watershed (Brooks and others 1997). As a result of the Hayman Fire, peak flows within the watersheds covered by the burned area are expected to be higher and occur quickly, but specific amounts are difficult to predict.

Fire Impacts on Surface Erosion

Surface erosion is the movement of individual soil particles. Forces that can initiate and sustain the movement of soil particles include raindrop impact (Farmer and Van Haveren 1971), overland flow (Meeuwig 1971), gravity, wind, and animal activity. Protection provided by vegetation, surface litter, duff, woody debris, and rocks reduces the impact of the applied forces and aids in deposition (McNabb and Swanson 1990; Megahan 1986).

Erosion is a natural process occurring on landscapes at different rates and scales, depending on geology, topography, vegetation, and climate. Erosion rates in dry land environments are often unsteady processes caused by infrequent, lone precipitation events (Brooks and others 1997). Landscape disturbing activities, including fires and fire management activities, often lead to the greatest erosion, which generally exceeds the upper limit of natural geologic erosion (Neary and Hornbeck 1994).

Soil erosion after prescribed burns can vary from under 0.4 to 2.6 tons per acre per year (0.1 to 6 Mg per ha per year), and in wildfires from 0.2 to over 49 tons per acre per year (0.01 to over 110 Mg per ha per year) (Megahan and Molitor 1975; Noble and Lundeen 1971; Robichaud and Brown 1999) (table 3).

Erosion on burned areas typically declines in subsequent years as the site stabilizes. Robichaud and Brown (1999) reported first-year erosion rates after a wildfire from 0.5 to 1.1 tons per acre (1.1 to 2.5 Mg per ha) decreasing by an order of magnitude by the second year, and to no sediment by the fourth, in an unmanaged forest stand in eastern Oregon. DeBano and others (1996) found that following a wildfire in ponderosa pine, sediment yields from a low severity fire recovered to normal levels after 3 years, but moderate and severely burned watersheds took 7 and 14 years, respectively. Consequently, postfire rehabilitation

Table 2—Effects of fire on peakflows in different forest habitat types (modified by Robichaud and others 2000).

Location	Treatment	Peakflow increase factor	Reference
Douglas-fir, OR	Cut 50%, Burn	+1.1	Anderson 1974
	Clearcut, Burn	+1.3	
	Wildfire	+1.4	
Chaparral, CA	Wildfire	+20.0	Sinclair and Hamilton 1955
		+870.0	Krammes and Rice 1963
		+6.5	Hoyt and Troxell 1934
Ponderosa, AZ	Wildfire	+5.0 Summer	Rich 1962
		+150.0 Summer	
		+5.8 Fall	
		+0.0 Winter	
Ponderosa, AZ	Wildfire	+96.1	Campbell and others 1977
	Wildfire, moderate	+23.0	DeBano and others 1996
	Wildfire, severe	+406.6	
Ponderosa, NM	Wildfire	+160.0	Bolin and Ward 1987
Mixed Conifer, AZ	Wildfire	+7.0	Neary and Gottfried 2001
Mixed Conifer, CO	Wildfire	+140.0	Moody and Martin 2001

Table 3—Published first-year sediment losses after prescribed fires and wildfires (modified from Robichaud and others 2000).

Location	Treatment	Sediment loss		Reference
		t ac^{-1}	*Mg ha^{-1}*	
Ponderosa pine, CA	Control	<0.0005	<0.001	Biswell and Schultz 1965
	Prescribed fire	<0.0005	<0.001	
Ponderosa pine, AZ	Control	0.001	0.003	Campbell and others 1977
	Wildfire	0.6	1	
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	6	Noble and Lundeen 1971
P-pine/Doug.-fir, ID	Clearcut and wildfire	92	120	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	

treatments that have an impact the first year can be important in minimizing damage to both soil and watershed resources.

Nearly all fires increase sediment yield, but wildfires in steep terrain produce the greatest amounts (12 to 165 tons per acre, 28 to 370 Mg per ha) (table 3). Noble and Lundeen (1971) reported an average annual sediment production rate of 2.5 tons per acre (5.7 Mg per ha) from a 900 acre (365 ha) burn on steep river break lands in the South Fork of the Salmon River, ID. This rate was approximately seven times greater than hillslope sediment yields from similar, unburned lands in the vicinity.

While earlier 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 2001), we have relatively little data on the different factors that control the magnitude of these increases, or the rate at which these elevated runoff and erosion processes recover to background levels. In the absence of such information, it is challenging to predict the amounts of runoff or erosion that are likely to occur after a given fire, or a priori identify those areas that are most susceptible to high runoff and erosion rates should a fire occur. Hence, it is difficult to accurately assess the hazards to life and properties after a given area burns, such as with the Hayman Fire, or identify those areas that should have the highest priority for treatment.

Fire Impacts on Sediment Yield and Channel Stability

A stable stream channel reflects a dynamic equilibrium between incoming and outgoing sediment and streamflow (Rosgen 1996). Increased erosion after fires can alter this equilibrium by transporting additional sediment into channels (aggradation). However, increased peakflows that result from fires can incise headway areas and produce channel erosion (degradation). Sediment transported from burned areas as a result of increased peakflows can adversely affect aquatic habitat, recreation areas, roads, buildings, bridges, and culverts. Deposition of sediments alters habitat and can fill in lakes and reservoirs (Rinne 1996; Reid 1993).

Channel incision and gully formation are important sources of sediment in the Colorado Front Range (Moody and Martin 2001). The increase in surface runoff can lead to channel initiation in formerly unchannelled areas and to new cutting and gullying in existing small channels. Montgomery and Dietrich (1994) found channel initiation occurred under less severe conditions when runoff was increased by road drainage. The increased runoff after wildfires presumably creates an analogous situation, and this generally results in an upslope extension of channel heads and incision in smaller channels. 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.

Fire Impacts on Water Quality

Increases in streamflow after fire can result in small to substantial effects on the physical and chemical quality of streams and lakes, depending on the size and severity of the fire (DeBano and others 1998). Higher streamflows and velocities result in additional transport of solid and dissolved materials that can adversely affect water quality for human use and damage aquatic habitat. After fires, suspended sediment concentrations in streamflow can increase due to the addition of ash and silt-to-clay sized soil particles in streamflow. High turbidity reduces water quality and can adversely affect fish and other aquatic organisms. It is often the most easily visible water quality effect of fires (DeBano and others 1998). Less is known about turbidity than sedimentation in general because it is difficult to measure, highly transient, and extremely variable.

Undisturbed forest, shrub, and range ecosystems usually have tight cycles for minerals, resulting in low concentrations in streams. Disturbances that interrupt uptake by vegetation may affect mineralization, microbial activity, nitrification, and decomposition. These processes result in the increased concentration of inorganic ions in soil that can be leached to streams via subsurface flow (DeBano and others 1998). Nutrients carried to streams can increase growth of aquatic plants, reduce the potability of water supplies, and potentially produce toxic effects on aquatic organisms.

Conditions of the Hayman Fire Area and BAER Team Evaluation

The Burned Area Report filed by the Burned Area Emergency Rehabilitation (BAER) Team describes the hydrological conditions in the Hayman Fire area, values at risk, and their emergency rehabilitation recommendations (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

Burn severity was classified following Ryan and Noste (1983) and Hungerford 1996 (table 1). However, in the Hayman Fire area, there are many areas where the ground conditions appear more like the moderate condition than the high condition, but there are no needles remaining on trees. The ecological and watershed implications of the lack of needle cast potential are severe: (a) no protection of soil from detachment by water; (b) no needles to moderate surface soil temperature and moisture, which may lead to longer revegetation recovery times; and (c) no needles to provide immediate addition of soil organic matter. The lack of needles, combined with a thin but strong water repellent surface layer, may lead to rapid runoff and substantial soil erosion during intense storms. Consequently, these areas are classified as high burn severity.

The large postfire rehabilitation effort required in response to the Hayman Fire reflects the fact that 35 percent of the area is classified as high burn severity. Table 4 delineates the acreage and percent of total area of each burn severity classification. Figure 1 maps the burn severity areas within the Hayman Fire perimeter.

Soils

The landforms of the Hayman Fire area are dominantly mountain slope lands (15 to 80 percent) in steep V-shaped valleys, and the slopes are highly dissected with Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) vegetation. The parent material on the Hayman Fire area is Pike Peak granite, which weathers to coarse gravel and fine sand in the soil profile. The coarse-textured parent material provides a moderately acidic substrate for soil development. The soils that develop on these coarse-textured parent materials are all highly susceptible to erosion, sheetwash, rilling, and gullying when exposed to direct impact of rain.

Table 4—Burn severity areas and erosion rates determined by the Hayman Fire BAER team.

Burn severity	Area		Erosion rate
	acres, ha	*percent*	*tons/acre, Mg/ha*
Unburned	21,200 (8,600)	15	1 (2.2)
Low	46,700 (18,900)	34	45 (100)
Moderate	21,700 (8,800)	16	70 (160)
High	47,900 (19,400)	35	140 (310)

The soils in the area consist predominantly of two soil types, Sphinx and Legault. Rock outcrops (15 percent of the total area) dominate in some areas and alluvium soil deposits are found in some 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 soil is a dark grayish brown, very gravelly coarse sandy loam that has also formed from weathered Pike Peak granites. It is found on north-facing aspects and higher elevations of the mountainsides. 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.

The BAER Team used erosion data from the nearby Turkey Creek and Buffalo Creek Fires to estimate the postfire erosion rate for the moderate and high burn severity areas, while the Water Erosion Prediction Project (WEPP) model as modified for disturbed forest land (Elliot and others 2001) was used to adjust the erosion rates for the low severity and unburned parts of the fire. Field review of the burned area was used to verify conditions and assumptions used in the modeling. Predicted erosion rates for the different severity classes are presented in table 4. The BAER Team estimated annual erosion rate for the Hayman Fire area is 86 tons per acre (193 Mg per ha) based on a weighted average of the erosion rates by severity class and acreage in each group.

Hydrology

The Hayman Fire was within the South Platte River drainage. The South Platte River flows from southwest to the northeast through the interior of the burn (fig. 1). Figure 2 shows the 11 sixth-level watersheds (area of land drained by sixth level stream—generally 10,000 to 30,000 acres, 4,000 to 12,000 ha) affected by the fire, which include perennial tributaries such as Brush Creek, Fourmile Creek, Goose Creek, Horse Creek, Saloon Creek, Turkey Creek, West Creek, and Wigwam Creek. Annual precipitation is composed of snowfall during the winter and convective rainstorms during the summer.

Cheesman Reservoir is a major impoundment on the South Platte River near the center of the burn. Strontia Springs Reservoir is another important impoundment on the South Platte River downstream of the burned area. The Denver Water Board owns and operates these reservoirs as important 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 dam, while roughly 56 percent of the burned area drains directly into the Cheesman or the South Platte River upstream of the reservoir (fig. 2). In 2000 the Upper South Platte Watershed Protection and Restoration Project identified the area as "at risk" to catastrophic wildfire (USDA Forest Service 2000). Recent forest management has included firebreak development along Fourmile Creek and Horse Creek. Other areas burned by the Hayman Fire had been proposed for fuel reduction treatment.

Runoff Modeling

The runoff curve number (RCN) model "WILDCAT4" (Hawkins and Greenberg 1990) was used by the BAER Team to estimate prefire and postfire runoff from small watersheds. The model uses National Resource Conservation Service (NRCS) curve numbers to predict runoff "in a timed pattern from design rainstorms, and uses triangular unit hydrographs to route the rainfall excess to make hydrographs. There is no channel routing involved" (Hawkins and Greenberg 1990).

Design Storm and Runoff Predictions—The design storm selected to evaluate prefire and postfire hydrology for watersheds within the burned perimeter is the 25-year, 1-hour storm over an area of 5 mi^2 (13 km^2). This translates into a predicted precipitation for this event of 1 inch (25 mm) in 1 hour. The distribution of rainfall intensities over the 1-hour (33 percent of the rain falls in the first 5 minutes with declining intensity for the rest of the hour) is based on local information of short duration rainfall relations (Arkell and Richards 1986). Figure 3 illustrates the distribution of the design storm, which is typical for a summer thunderstorm in this region.

The NRCS curve numbers used for various watershed conditions are as follows: rock = 90, unburned = 80, low severity = 85, and moderate and high severity = 95. The time of concentration was calculated using the following relationship (USDA Forest Service 2002):

Time of concentration = (channel length)1.15 ÷ [7700*(elevation difference)0.38]

The model predicted substantial increases in peak flow events for watersheds where a high percentage of the area was moderate to high burn severity. Predicted flows from 10 of the 80 modeled watersheds would exceed 500 cfs mi^{-2} (5.4 m^3 s^{-1} km^{-2}) and for three watershed flows would exceed 600 cfs mi^{-2} (6.5 m^3 s^{-1} km^{-2}). The average prefire predicted runoff was 75 cfs mi^{-2} (0.8 m^3 s^{-1} km^{-2}) and the predicted postfire runoff was 290 cfs mi^{-2} (3.1 m^3 s^{-1} km^{-2}). Figure 4 illustrates the distribution of the watersheds within selected categories. Table 5 summarizes the postfire runoff predictions for three main areas of the fire: (1) upstream of Cheesman Reservoir, (2) downstream of

Table 5. Average predicted postfire runoff for selected areas as modeled by the Hayman Fire BAER Team.

General area description	Average watershed size[a]	Average predicted runoff
	mi^2, km^2	*cfs mi^{-2}, $m^3\ s^{-1}\ km^{-2}$*[b]
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 watershed modeled within the selected area.

[b]Produced by the 25-year, 1-hour design storm, 1 inch per hour over 5 $mile^2$ (25 mm per hour over 13 km^2). The design storm is limited to an area of 5 $mile^2$ (13 km^2).

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. 2).

Model Validation—The predicted postfire runoff values are consistent with data collected in the Colorado Front Range with similar characteristics. Moody and Martin (2001) demonstrated that significant runoff events (flash floods) occurred following the Buffalo Creek Fire when the maximum 30-minute rainfall intensity (I_{30}) exceeded 0.4 inch per hour (10 mm per hour). Using the Spring Creek data for calibration, an I_{30} of 2.0 inches per hour (50 mm per hour) yielded 480 cfs mi^{-2} (5.2 $m^3\ s^{-1}\ km^{-2}$) 1 year after the fire, and an I_{30} of 1.8 inches per hour (45 mm per hour) intensity yielded 300 cfs mi^{-2} (3.2 $m^3\ s^{-1}\ km^{-2}$) 2 years after the fire.

The selected design storm distribution for the Hayman Fire includes an I_{30} of 1.7 inches per hour (43 mm per hour), which is similar to the higher intensities recorded by Moody and Martin (2001) in Buffalo Creek. The WILDCAT4 modeling for the Hayman Fire predicted normalized flows that are in line with measured precipitation events and the resulting runoffs from the Buffalo Creek Fire.

Water Quality

Water quality will be reduced due to the fire and might include increases in organic carbon, ash, and sediment. These increases will likely be measurable within several smaller drainage basins and within the South Platte River above and below Cheesman Reservoir. A large amount of sediment will likely become mobile due to the soil type and steep slopes within the burn area.

The sediment delivery potential is based on postfire monitoring of the Buffalo Fire (Moody and Martin 2001), which demonstrated that approximately 15 acre feet (24,000 $yard^3$, 18,500 m^3) of sediment was delivered to Strontia Springs Reservoir for each square mile of burn area over the 5 years following the fire. This value—15 acre-feet mi^{-2} (24,000 $yard^3$ mi^{-2}, 71,000 m^3 km^{-2}) over the 5-year recovery 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, 560 km^2), the potential volume of sediment delivered to streams may be as great as 3,500 acre feet (5.6 million $yard^3$, 4.3 million m^3) over the 5-year recovery period.

The sediment delivery potential has been 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; fig. 2). Assuming a 5-year

Table 6—Potential sediment delivery to streams as modeled by the Hayman Fire BAER team.

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 CheesmanReservoir	83,000 (34,600)	130 (340)	1,950 (2,400,000)
Below CheesmanReservoir (west)	21,700 (8,800)	34 (90)	510 (600,000)
Below CheesmanReservoir (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 Fire (Moody and Martin 2001) – The potential rate of 15 acre-feet $mile^{-2}$ (7,100 m^3 km^{-2}) during the 5-year recovery period includes storms of higher intensity than the design storm.

sediment yield of 15 acre-feet mi^{-2} (24,000 $yard^3$ mi^{-2}, 71,000 m^3 km^{-2}), approximately 1,500 acre feet ft (2.4 million $yard^3$, 1.8 million m^3) of sediment could enter the South Platte River below Cheesman Reservoir over the 5 years. Potentially, 1,950 acre feet (3.1 million $yard^3$, 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. Sediment delivery to Cheesman Reservoir over the first 5 years following the fire is predicted to be 1,950 acre feet (3.1 million $yard^3$, 2.4 million m^3). The storage capacity of Cheesman is approximately 79,800 acre feet (130 million $yard^3$, 98 million m^3). The sediment delivered to Cheesman Reservoir as a result of the Hayman Fire is predicted to be less than 3 percent of the reservoir storage capacity.

The storage capacity of Strontia Springs Reservoir is about 7,600 acre feet (12.3 million $yard^3$, 9.4 million m^3). Roughly 1,530 acre feet (2.5 million $yard^3$, 1.9 million m^3) of sediment is predicted to enter the South Platte River below Cheesman; however, only a portion of that is predicted 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. Consequently, the river should act to buffer sediment delivery to Strontia Springs Reservoir.

Risk Assessment

Values at risk identified by the BAER Team include the following:

Increased Flood Flows—Stream flows will increase after fires 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. Although the magnitude of increase varies, 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 safety of recreational travel and camping. Additionally, increased 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.

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 Buffalo Creek Fires demonstrate that debris flows have greater potential of occurrence after high severity burns.

Water Quality—Trout Creek and the South Platte River above Cheesman Reservoir are on the 1998 State 303(d) list for sediment. Goose Creek, Horse Creek, Taryall Creek, and Trail Creek are on the 1998 State Monitoring and Evaluation list for sediment. The South Platte River is the conveyance system for the public water supply of Denver. There are also domestic wells within and around the burned area that may be impacted. In addition, reduced water quality within the burn 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 Recommendations

The BAER Team delineated the specific treatments and locations where these treatments should be applied (USDA Forest Service 2002). The BAER Team report included the following treatment objectives:

- Reduce erosion by providing ground cover and increasing 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 Forest Service-owned burned acreage.
- Protect roads and crossings from flood flows.
- Spot-treat locations of noxious weeds within the fire area, to reduce the threat of significant expansion and invasion of new 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.

Descriptions of the various erosion control treatments are included below. Figure 5 shows the location of selected treatment applications within the burned area. The associated costs for these treatments are listed in table 7.

Table 7—Postfire emergency rehabilitation treatment costs for the Hayman Fire.

Land treatments	National Forest System lands			
	Units	Unit cost ($)	Unit (#)	Treatment cost ($)
Road hydromulching	Acres	1,803	1455	2,623,365
Aerial hydromulching	Acres	3,003	1500	4,504,500
Aerial dry mulching	Acres	500	12000	6,000,000
Mechanical scarification	Acres	43	9800	416,500
Hand scarification	Acres	880	4200	3,696,000
Heritage sites	Sites	670	2	1,340
NFS-Above private land treatments	Sites	2,073	12	24,876
Noxious weed treatments	Acres	210	495	103,950
Colorado Cares treatment	Project		125	8,700
Flood warning signs	Project			2,600
Flood warning system	Project			67,350
Seeding	Project			407,000
Total				**$17,856,181**

Land Treatments

- *Ground-based hydromulching with seed (fig. 6):* For 1,500 acres (607 ha). From existing roads and high severity burn areas that can be reached by existing roads, truck-mounted hydromulching will occur for an area within 300 feet (91 m) either side of the road. Ground cover amounts will be 2,000 lb per acre (2.24 Mg per ha), and seed will be included in the mix as described in table 8.
- *Aerial hydromulching with seed (fig. 7, 8, 9):* For 1,500 acres (610 ha). For the high severity burn areas draining to the South Platte River below Cheesman dam, which cannot be reached by existing roads, aerial hydromulching will occur. The intent of the treatment is to prevent loss of topsoil, improve infiltration rates and replace organic litter consumed by the fire. The focus will be on ridge-tops and upper one-third slope positions with slopes of 20 to 60 percent. Application rate will be 2000 lb per acre (2.24 Mg per ha), and the mulch and tackifier to be used by the contractor will be suitable for 20 to 60 percent slopes. Seed will be included in the mix as described in table 8.
- *Aerial dry mulching with seed (fig. 10, 11):* For 4,500 acres (1,800 ha). High severity fire areas above Cheesman dam that cannot be reached by existing roads, dry mulching will occur. The intent of the treatment is to prevent loss of topsoil, improve infiltration rates and replace organic litter consumed by the fire. Focus will be on ridge-tops and upper one-third of the slopes. Application rate will be 2000 lb per acre (2.24 Mg per ha), and the mulch used by the contractor will be suitable for 20 to 60 percent slopes. Seed will be included in the mix as described in table 8.
- *Noxious weed spot-treatment and biologic control:* For 195 acre (79 ha). Apply herbicide spot treatments to known weed infestations. Targeted sites have been ground-truthed and pose a threat for the establishment, seed set, and expansion into vulnerable fire areas. The purpose of the treatment is to prevent the establishment and expansion of noxious weeds in the burned areas and into uninfested areas directly outside of the burn. All treatments will comply with the Pike and San Isabel National Forest Noxious Weed Environmental Assessment application guidelines.
- *Mechanical scarification by all-terrain vehicles, with seed (fig. 12):* For 9,800 acres, 4,000 ha). Scarification and seeding will occur on selected

Table 8—Seeding variety recommended by the BAER team for the Hayman Fire area.

Grass	Variety	Mix amount	Broadcast rate PLS	Seeds
		percent	*lbs/acre, kg/ha*	*# feet^{-2}, # m^{-2}*
Cereal Rye (*Lolium multiflorum*)	—	100	60 (67)	24 (260)

high severity-burn areas on slopes less than 20 percent that pose a threat to downslope values and onsite soil erosion. Areas will be treated with a chain link harrow with 4 inches (10 cm) teeth pulled behind an all terrain vehicle on the contour and seeded with the mix as described in table 8. The harrow will also break up the water repellent soil layer and increase infiltration.

- Flood warning signs/system: Twenty-five "Flash Flood Warning" signs were installed at key locations across the fire, primarily at ingress points into the burn area. In addition, a flood-warning system using Remote Automated Weather Stations (RAWS) was installed.
- *"Colorado Cares Day" scarification, seeding and mulching (fig. 13):* For 125 acres (50 ha). For the "Colorado Cares Day," a variety of treatments were installed to use the services of some 1,200 volunteers. Scarification was done using hand-rakes, whirly-bird seeders were used to spread the seed, and mulch was applied by hand.
- *Spot treatment of at-risk heritage sites:* Two heritage sites are at risk from high flows and erosion. Strategically placed straw bales with rebar anchoring will be placed to divert anticipated flood flows away from the sites.
- *Treatments on burned National Forest lands located above private land:* There is a considerable amount of private land within the Hayman Fire area. In many locations, moderate and high severity burn occurred on National Forest System property directly above and upslope of private homes. During the BAER field assessment, six sites were identified for special treatment (sandbag deflectors, directional felling) in addition to the slope treatments that are to occur farther upslope. At an additional 10 sites, upslope aerial hydromulching and scarification should reduce the risks to these sites.
- *Seeding:* To ensure the quality of seed used in this rehabilitation effort, the USDA Forest Service will obtain all of the seed for the project. The Forest Service will make sure that the seed has been tested for noxious weed content and inert matter within the previous 120 days. All seed mixes will be certified noxious weed free.
- *Channel treatments (fig. 14):* The BAER Team recommended no channel treatments. However, the Denver Water Board is using strawbale check dams in tributaries above Cheesman Reservoir. Therefore, a discussion of their effectiveness is presented in section three.

<u>Road and Trail Treatments</u>

- *Armored ford crossings:* For 14 stream crossings. For stream crossings on roads that need to be kept open for access and public safety, the sites will be modified to safely pass anticipated flood flows. Crossing structures will not be up-sized, but armoring will be installed so the crossing does not wash out. Construction of a nearby dip to capture any flow that would go down the road or the ditch is included in this treatment.
- Road maintenance: For 120 miles (190 km). To prepare for the anticipated flows from the fire area, heavy maintenance will be performed on forest roads. This will include road grading, culvert and ditch cleaning, and reinstallation of rolling dips.
- *Storm patrol:* A patrol will drive forest roads immediately following storm events to check for culvert plugging or other drainage problems.
- *Riprap:* At several locations, anticipated flows will endanger the edges of important roads. At six sites, riprap will be strategically placed to protect the road edge.
- *Road closures:* Extensive temporary road closures are necessary due to safety concerns (hazard trees, boulders rolling from steep burned slopes, and aerial rehabilitation treatment applications), to possible road washouts and flash floods, and to aid in the rehabilitation of burned lands by simply reducing use. Closure methods will include gates, large waterbars, boulders, and signs. Portable barricades will be needed for closure of roads due to storms.

Effectiveness of Postfire Rehabilitation Treatments—the Current Knowledge

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 about most postfire emergency rehabilitation treatments (MacDonald 1988; Robichaud and others 2000).

Hillslope Treatments

Hillslope treatments such as grass seeding, contour-felled logs, and mulches are intended to reduce surface runoff and keep soil in place. These treatments are regarded as a first line of defense against postfire erosion and unwanted sediment deposition.

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, increases infiltration, and improves moisture retention underneath it, benefiting seeded grasses.

Straw mulch applied at a rate of 0.9 ton per acre (2 Mg per ha) significantly reduced sediment yield on burned pine-shrub forest in Spain over an 18-month period with 46 rainfall events (Bautista and others 1996). Sediment production was 0.08 to 1.3 tons per acre (0.18 to 2.9 Mg per ha) on unmulched plots but only 0.04 to 0.08 ton per acre (0.09 to 0.18 Mg per ha) on mulched plots.

Miles and others (1989) studied the use of wheat straw mulch on the 1987 South Fork of the Trinity River Fire on the Shasta-Trinity National Forest in California. Wheat straw mulch was applied to fill slopes adjacent to perennial streams, firelines, and areas of extreme erosion hazard. Mulch applied at rates of 2 tons per acre (4.5 Mg per ha), or 1 ton per acre (2.2 Mg per ha) on larger areas, reduced erosion 6 to 10 yard^3 per acre (11 to 19 m^3 per ha). They considered mulching to be highly effective in controlling erosion.

Mulch was evaluated in two quantitative monitoring reports and found to be effective. For example, Faust (1998) collected only 0.8 ton per acre (1.8 Mg per ha) of sediment below a slope mulched and seeded with oats as compared to 5.8 tons per acre (13 Mg per ha) below a slope that had only been seeded with oats.

Dean (2001) used silt fence sediment traps (Robichaud and Brown 1999) to compare treatments for two monsoon seasons after the 2000 Cerro Grande Fire on the Bandelier National Monument and the Santa Fe National Forest in New Mexico. Although precipitation during the 2 years of the study was well below normal, the aerial seed/straw mulch sediment trap yields were 70 percent less than the no-treatment sediment traps during the first year and 95 percent less during the second year. The sediment trap yields for the aerial seed/straw mulch/contour-felled logs treatment were 77 percent less the first year and 96 percent less the second year. These results indicate that the contour-felled logs did not provide any statistically significant improvement over the straw mulch alone. In addition, the ground cover transect studies showed that aerial seeding without added straw mulch provided no appreciable increase in ground cover over no treatment at all (Dean 2001).

Mulch is most effective on gentle 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 very steep slopes, rain can wash some of the mulch material downslope. Punching it into the soil, use of a tackifier, or felling small trees across the mulch may increase onsite retention.

Mulch is frequently applied to improve 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. Use of straw from pasture introduces exotic grass seed. Forests are now likely to seek "weed-free" mulch such as rice straw. Due to the cost and logistics of mulching, it is usually used in high value areas, such as above or below roads, above streams, or below ridge tops. There is concern that thick mulch inhibits native shrub or herb germination. Shrub seedlings have been observed to be more abundant at the edge of mulch piles, where the material was less than 1 inch (2.5 cm) deep.

Mulch can be applied most easily where road access is available because bales must be trucked in, although they can be transported and distributed by helicopter. The use of helicopters to spread mulch is relatively new in postfire emergency rehabilitation. Effectiveness of mulch depends on even application and consistent thickness. 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 burning. This lack of effectiveness can be attributed to the intense rain event that overwhelmed all the treatment efforts. In the second year after burning, rainfall was spread over several smaller events, and the sediment yields in the both the mulched and contour-log erosion barrier areas were significantly less than the sediment yields in untreated areas. Although mulching was somewhat more effective than contour-log erosion barriers, seeding had no significant effect on sediment yields at the hillslope scale (Wagenbrenner and others 2002).

Hydraulic Mulch—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 helps reduce erosion and fosters plant growth. Hydraulic mulches generally consist of wood fibers, tackifers, soil binders, viscosity stabilizers, and water. Most application of hydraulic mulches has been with truck-mounted equipment on road cut and fill slopes, construction sites, and recreation facilities. Several State Department of Transportation engineers have tested effectiveness of various products on road cuts and fills. For unburned soils an application of 3,500 lb per acre (3.9 Mg per ha) of hydraulic mulch reduced erosion by 97 percent compared to bare soil under laboratory rainfall simulators (SDSU 2002).

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. More recently PAM products have been introduced to hydraulic mulches/seed mixes to increase binding of soil particles. These products have been used on road cut and fills as well as undeveloped sloped areas to stabilize soils and reduce erosion while grass seeds germinate.

The effectiveness of PAM for treatment of burned areas has not been well tested or documented. In a preliminary study done with simulated rainfall on the Hayman Fire area, MacDonald (personal communication 2002) reported that sediment production from a plot treated with PAM followed the same pattern (a sharp spike followed by relatively constant erosion rates) as untreated plots; however, the plot with PAM had a much smaller spike followed by a slow decline in erosion rates until about 30 minutes into the experiment at which point the erosion rate began to progressively increase. Although these preliminary results suggest some 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.

Scarification—Scarification is a mechanical soil treatment aimed at improving infiltration rates in water repellent soils. Scarification may increase the macro porosity of the soil and physically break up the water repellent layer, thus increasing the amount of rainfall that infiltrates into the soil. Hand tools (McClouds) are commonly used in inaccessible or steep terrain, whereas all-terrain vehicles (ATV) and tractors have been used on gentle slopes to drag a harrow behind to break up the water repellent soil layers. Depths of the hand tools are generally shallow (0.5 to 1.5 inches, 1.3 to 3.8 cm) whereas machine pulled harrows or rippers can be 1 to 12 inches (2.5 to 30 cm) deep.

Scarification was judged to be an "excellent" treatment for roads, firebreaks, and trails but less effective on hillslopes (Robichaud and others 2000). This technique may add roughness to the soil and promote infiltration. It may be successful for site-specific circumstances such as compacted or water repellent soil areas, but not economically feasible on large areas or safe to do on slopes greater than 30 to 45 percent. Hand tools and vehicle-pulled harrows (4 inches, 10 cm long harrow teeth) were used on the Hayman Fire. Water repellent layers may be shallow (0.5 inch, 1.3 cm) or deep (6 inches, 15 cm). Therefore, for this treatment to be effective the depth of the water repellent layer must be evaluated and proper equipment used to break up that layer.

Aerial Seeding—Historically, the most common BAER practice has been broadcast seeding of grasses, usually from aircraft. Rapid vegetation establishment has been regarded as the most cost-effective method to promote rapid infiltration of water and to keep soil on hillslopes and out of channels and downstream areas (Miles and others 1989; Noble 1965; Rice and others 1965). Grasses are particularly desirable for this purpose because their extensive, fibrous root systems increase water infiltration and hold soil in place. Fast-growing nonnative species have typically been used. They are inexpensive and readily available in large quantities when an emergency arises (Agee 1993; Barro and Conard 1987; Miles and others 1989).

However, the studies examined by Robichaud and others (2000) suggest that grass seeding does not assure increased plant cover during the critical first year after burning. A wide variety of grass species, or seed mixes, and application rates were evaluated. Better cover, and thereby better erosion control, can be expected in the second and subsequent years. Grass seeding was usually perceived as "effective" if: (1) it produced at least 30 percent cover by the end of the first growing season; (2) seeded species comprised a significant amount of the total plant cover at the end of the first growing season; or (3) less sediment movement was measured compared to unseeded plots or watersheds.

The most extensive study of annual ryegrass effects on erosion and vegetation response was conducted on five sites burned in hot prescribed fires and a wind-driven wildfire in coastal southern California (Beyers and others 1998a,b; Wohlgemuth and others 1998). At all five sites, postfire erosion was greatest during the first year after fire and was not significantly affected by ryegrass seeding (Wohlgemuth and others 1998). Seeding increased total plant cover the first year at only one site by about 1.5 percent, probably accounting for the lack of difference in erosion rates (Beyers and others 1998a). Average ryegrass cover reached 15 to 30 percent on some sites in the second year after burning. Native herbaceous plant cover and species richness were lower on seeded plots with high ryegrass cover (Beyers and others 1994, 1998b). Unlike some earlier studies, Beyers and others (1998a) did not find significantly lower shrub seedling density on seeded plots. In later postfire years, some sites had significantly less erosion on seeded than on unseeded plots, but this happened only after erosion rates had dropped to prefire levels, which occurred in as little as 2 years on some sites (Wohlgemuth and others 1998). A complete review of grass seeding effectiveness is provided in Robichaud and others (2000).

Contour-Felled Logs—This treatment involves felling logs on burned-over hillsides and laying them on the ground along the slope contour, providing mechanical barriers to water flow, promoting infiltration, and reducing sediment movement; the barriers can also trap sediment. The terms "log erosion barriers" or "log terracettes" are often used when the logs are staked in place and filled to prevent underflow (Robichaud and others 2000). Logs were contour-felled on 22 acres (9 ha) of the 1979 Bridge Creek Fire, Deschutes National Forest in Oregon (McCammon and Hughes 1980). Trees 6 to 12 inches (15 to 30 cm) dbh were placed and secured on slopes up to 50 percent at intervals of 10 to 20 feet (3 to 6 m). Logs were staked and holes underneath were filled. After the first storm event, about 63 percent of the contour-felled logs were judged effective in trapping sediment. The remainder were either partially effective or did not receive flow. Nearly 60 percent of the storage space behind contour-felled logs was full to capacity, 30 percent was half-full, and 10 percent had insignificant deposition. Common failures were flow under the log and not placing the logs on contour (more than 25° off contour caused trap efficiency to decrease to 20 percent). Over 1,600 yard^3 (1,225 m^3) of material was estimated to be trapped behind contour-felled logs on the 22 acres, or about 73 yard^3 per acre (135 m^3 per ha). Only 1 yard^3 (0.7 m^3) of sediment was deposited in the intake pond for a municipal water supply below. Miles and others (1989) monitored contour felling on the 1987 South Fork Trinity River Fire, Shasta-Trinity National Forest in California. The treatment was applied to 200 acres (80 ha) within a 50,000 acre (20,240 ha) burned area. Trees less than 10 inches (25 cm) diameter at breast height spaced 15 to 20 feet (4.5 to 6 m) apart were felled at rate of 80 to 100 trees per acre (200 to 250 trees per ha). The contour-felled logs trapped 0 to 0.07 yard^3 (0 to 0.05 m^3) of soil per log, retaining 1.6 to 6.7 yard^3 per acre (3 to 13 m^3 per ha) of soil onsite.

Contour-felled logs were judged to be effective in five monitoring reports (Robichaud and others 2000). Accumulation of sediment uphill of the barriers (Green 1990), lack of rilling in the treated area, or reduction in sediment collected downhill compared to an untreated plot were considered "effective" outcomes. For example, DeGraff (1982) measured "sediment trap efficiency" (STE) at 0.7 on slopes of less than 35 percent on the Sierra National Forest, meaning that 70 percent of the length of a log, on average, had accumulated sediment. Logs on steeper slopes exhibited an average sediment trap efficiency of 0.57. Griffith (1989) observed 1.5 tons per acre (3.4 Mg per ha) of sediment behind a silt fence below a watershed treated with contour-felled logs, compared to 10.7 tons per acre (24.2 Mg per ha) from an untreated watershed during the first postfire year on the Stanislaus National Forest. Both watersheds were salvage-logged the following year, and sediment output increased to 10 tons per acre (23 Mg per ha) on the treated and over 34 tons per acre (77 Mg per ha) on the untreated watershed. Several reports from the first few years after the Foothills Fire on the Boise National Forest in Idaho stated that no significant amounts of sediment were produced from any of several small watersheds treated with contour-felled logs, whether or not they were salvage-logged (Maloney and Thornton 1995). The reports noted that the area experienced no major thunderstorms until late summer 2 years after the fire.

Channel Treatments

Channel treatments are designed for use in ephemeral or small-order channels to prevent 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 has been published on channel treatments than on hillslope methods (Robichaud and others 2000).

Straw Bale Check Dams—Miles and others (1989) reported on 1,300 straw bale check dams installed after the 1987 South Fork Trinity River Fire on the Shasta-Trinity National Forest in California. Most dams were constructed with five bales. About 13 percent of the straw bale check dams failed due to piping under or between bales or undercutting of the central bale. Each dam stored an average 1.1 yard^3 (0.8 m^3) of sediment. The researchers felt that filter fabric on the upside of each dam and a spillway apron would have increased effectiveness. They considered straw bale check dams easy to install and highly effective when they did not fail. Collins and Johnston (1995) evaluated the effectiveness of straw bales on sediment retention after the Oakland Hills Fire. About 5,000 bales were installed in 440 straw bale check dams. Three months after installation, 45 percent of the check dams were functioning. This decreased to 40 percent by 4.5 months, at which time 9 percent were side cut, 22 percent were undercut, 30 percent had moved, 24 percent were filled, 12 percent were unfilled, and 3 percent were filled but cut. Sediment storage for all the check dams amounted to 55 yard^3 (42 m^3) behind straw bale check dams and another 122 yard^3 (93 m^3) on an alluvial fan.

Goldman and others (1986) recommended that the drainage area for straw bale check dams be kept to less than 20 acre (8 ha). Bales usually last less than 3 months, flow should not be greater than 11 cfs (0.3 m^3 s^{-1}), and bales should be removed when sediment depth upstream is one-half of bale height. More damage can result from failed barriers than if no barrier were installed (Goldman and others 1986).

Fites-Kaufman (1993) reported on the failure of straw bale, log, and sandbag check dams after the Cleveland Fire on the Eldorado National Forest, California. Thirty percent of straw bale check dams failed from undercutting and blowouts compared to only 3 percent of log and sand bag check dams. Failures occurred in narrow, steep drainages where only two bales composed the check dam. Downstream support from rocks or logs reduced the failure rate. No estimates of the sediment trapping efficiency were made.

Niehoff (1995) noted that straw bale check dams had mixed success after the 1986 Mary-Mix Fire on the Clearwater National Forest in Idaho. Straw bales placed in low to moderately incised first- and second-order channels were in place and functioning to stabilize stream grade 1 and 9 years postfire. Straw bale check dams placed in deeply incised drainages were completely blown out at the end of the first year.

Kidd and Rittenhouse (1997) reported that 800 straw bale check dams installed in channels after the Eighth Street Fire on the Boise National Forest, Idaho, had a 99 percent structural integrity rate. Although these structures were still being monitored, no estimates of sediment trapping efficiency were available. On a scale of 1 to 10, straw bale check dams were rated 9 in terms of their effectiveness. Observations of log and rock check dams installed after the Cleveland Fire on the Eldorado National Forest, California, indicated that they were effective in trapping sediment and held up well over time (Parsons 1994). No estimates of sediment storage were made.

Road Treatments

BAER road treatments include various practices aimed at increasing the water and sediment processing capabilities of roads and road structures, such as culverts and bridges, in order to prevent large cut-and-fill failures and the movement of sediment downstream (Robichaud and others 2000). Road treatments include out sloping, gravel on the running surface, rocking ditches, culvert removal, culvert upgrading, roadway overflows, armored stream crossings, rolling dips, and water bars. The treatments are not meant to retain water and sediment, but rather to manage water's erosive force. Trash racks and storm patrols try to prevent culvert blockages due to organic debris, which could result in road failure that would increase downstream flood or sediment damage.

Furniss and others (1998) developed an excellent analysis of factors contributing to the failure of culverts used for stream crossings. Some 80 to 90 percent of fluvial hillslope erosion in wildlands can be traced to road fill failures and diversions of road-stream crossings (Best and others 1995). Because it is impossible to design and build all stream crossings to withstand extreme stormflows, the researchers recommended increasing crossing capacity to minimize the consequences of culvert exceedence as the best approach for forest road stream crossings. Comprehensive discussions of road-related treatments and their effectiveness can be found in Packer and Christensen (1977), Goldman and others (1986), and Burroughs and King (1989).

Boyd and others (1995) reported on the hydrologic functioning of roads and their channel structures within the Cleveland Fire in the Cleveland National Forest in California after a storm of 4+ inches (10+ cm) in 48 hours. An oversized culvert put in place after the fire successfully processed large chunks of wood and rocks. A nearby normal-sized culvert was repeatedly plugged during the storm, resulting in numerous overflows onto the road. Flanagan and Furniss (1997) described the reduction in flow capacity by partial blockage. During the same storm, Boyd and others (1995) observed that some correctly constructed postfire water bars did not have sufficient rocks or slash to dissipate the energy of the increased surface runoff. The resulting concentration and channelization of runoff produced small gullies and one large, entrenched gully.

Monitoring Postfire Rehabilitation Treatments

Monitoring the effectiveness of postfire rehabilitation treatments is important to determine if the treatments are functioning as desired. There are several components necessary to determine this. First, the objectives of monitoring must be identified, the possible methods discussed, and estimated costs determined. This section will describe various topics on monitoring protocols.

Implementation Monitoring

Implementation monitoring ensures that postfire rehabilitation treatments are implemented as planned. Implementation monitoring is designed to answer the question, "Did we do what we said we were going to do?" In the case of dry mulching, for example, implementation monitoring would check that the mulch was applied on the designated areas at the specified application rate. Implementation monitoring is a widely accepted procedure in the USDA Forest Service and other management agencies.

To be effective, implementation monitoring has to be conducted as the individual actions are being completed. In most cases the agency or landowner responsible for the work conducts the implementation monitoring. The number of activities after large fires is likely to necessitate additional personnel (inspectors) to conduct implementation monitoring. Close ties between the activity and the monitoring is 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. For example, different contractors may use different mixes of materials for hydromulching, or different procedures for scarifying the soil, and qualitative observations could be used to adjust how a treatment is being applied or even the design of the treatments.

Effectiveness Monitoring

Effectiveness monitoring ("Did the treatment accomplish what it was designed to do?") is essential for guiding future responses to wildfires. We lack information on the effectiveness of postfire rehabilitation treatments (Robichaud and others 2000) including BAER treatments, which means that funds are being spent with little understanding of the likely benefits. Because future wildfires are likely and 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 to determine: (1) the relative effectiveness of the different BAER treatments to reduce postfire runoff and erosion rates in a given area; (2) how the effectiveness of the different treatments varies over time; and (3) how the effectiveness of the different treatments varies with storm magnitude.

The large spatial and temporal variability of postfire runoff and erosion processes means that effectiveness monitoring has to be replicated within and between areas, and effectiveness monitoring should be required after all fires with extensive BAER treatments. These data will provide a better basis for future management decisions and allow a more rigorous assessment of the benefits from a given treatment. Recent changes in Federal land management agency policies now allow up to 10 percent of BAER funds to be used for monitoring, so there is no inherent reason why implementation and effectiveness monitoring should not be conducted after any wildfire with BAER treatments.

Monitoring as Part of the BAER Team Report—Implementation and effectiveness monitoring needs to be an explicit and required part of the BAER Team report, but for many BAER reports, monitoring is limited, resulting in no explicit feedback to management and no guidance as to what should be done after future wildfires (Robichaud and others 2000). A monitoring section should be a required component of all BAER reports that recommend actions to mitigate the effects of the fire. This should include an implementation monitoring program, and there generally should also be an outline for an effectiveness monitoring program. The people that designed the BAER treatments, because they are the most familiar with the area and the desired treatments, would be the best to do implementation monitoring.

Given the time and logistical constraints on the BAER Team, the team should not be expected to develop the details of a monitoring program. However, the monitoring section within the BAER report should 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. Robichaud and Brown (1999) recently published a hillslope erosion monitoring protocol and techniques guideline that may be useful for effectiveness monitoring. 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 implementation monitoring should be concomitant with the BAER treatments. Similarly, the effectiveness monitoring needs to be done as quickly as possible because the first storms typically pose the greatest risk to downstream resources, and we have few data on the immediate effectiveness of BAER treatments.

The three main components of a monitoring program are design, data collection, and reporting. For longer-term monitoring projects there will be several iterations of data collection and reporting, as an effective feedback loop necessitates the regular analyses and reporting of monitoring results (MacDonald 1994). Most effectiveness monitoring projects also will require more intensive data collection and a longer term commitment than implementation monitoring. Large fires place a heavy burden on the affected agency, and it becomes difficult for these personnel to take on the responsibility for implementing and monitoring all the treatments.

Given these issues, the National Forests and other landowners may find it beneficial to partner with Forest Service researchers, universities, or other agencies. This partnership is particularly critical for developing a sound effectiveness monitoring program, as effectiveness monitoring is typically more difficult and time-consuming than implementation monitoring (MacDonald and others1991; MacDonald 2000). Additionally, treatments may be effective only for a certain range of storm events; thus the results of the same monitoring program in the same area may yield different results if the areas are subjected to a different sequence of storm events. 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.

Untreated Areas Needed for Comparison—To evaluate the effectiveness of postfire rehabilitation treatment(s), one must have a basis for comparison. Burned but untreated areas provide that baseline. Therefore, the BAER report should explicitly designate areas not to be treated, and these areas can be used to assess both short and long effectiveness of treatments as well as ecosystem response to the fire (see Fire Effects section). The untreated areas need not be large, but they should be as representative and comparable as possible to the areas that are 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 areas represented by each treatment.

Open Monitoring Program—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 sound monitoring programs are needed to guide future management actions. Public reporting of monitoring data is important to show that the Forest Service and other management agencies are attempting to evaluate the effects of their actions. An open and transparent presentation of the monitoring results allows concerned agencies and individuals to make their own judgments based on data rather than hearsay or supposition. By collecting and reporting monitoring data, the current debate over land management actions will be placed on a more objective basis, and this should also reduce the stridency of this debate.

Current Monitoring in the Hayman Fire Area—Recently established monitoring sites within the Hayman Fire area will, in addition to comparing treatment effectiveness, provide effectiveness monitoring for the those treatments that were applied for rehabilitation.

Robichaud (personal communication 2002) has recently established six small watershed monitoring sites (7 to 10 acres each) within high burn severity areas of the Hayman Fire Area. Four of the six small watersheds have been or will be differentially treated: (1) aerial hydromulching, (2) aerial dry mulch, (3) contour-felled logs, and (4) salvaged logged. 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 feet^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 (personal communication 2002) is also monitoring sites within the Hayman Fire area. At the watershed scale, 2.5 feet (0.75 m) H-flumes have been established in Saloon Gulch (840 acres, 340 ha) and Brush Creek (1,500 acres, 620 ha) where prefire and postfire data have been collected. At the hillslope scale, several sites (1 acre, 0.4 ha) using paired swales (one control and one treated) have been established in Upper Saloon Gulch and Schoonover Creek areas. The treatments being monitored and compared are: (1) dry mulch, (2) ground-based hydromulching, (3) hand scarification and seeding, (4) aerial hydromulch, (5) dry PAM application, and (6) wet PAM application.

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. Gaps in site-specific information available to the Hayman BAER team have been identified. In most cases these gaps are similar for other burned areas as well as for the Hayman Fire area. These gaps include:

- Knowledge of return intervals for short-duration, high-intensity thunderstorms, and how storm magnitudes vary with increasing areal 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 and may cause flash flooding and mobilizing large amounts of bedload and suspended sediments. Although this response has been documented in the literature, our knowledge and modeling ability of this response, especially for short-duration high-intensity storms, is not well established. Additionally, review of the literature on rehabilitation treatment effectiveness indicates that data on reducing runoff and erosion is limited. Knowledge of treatment effectiveness, specifically of newer treatments such as those used on the Hayman Fire area, is lacking. These treatments include hydromulch, aerial dry mulch, and scarification. Two of the authors of this project have monitoring projects on the Hayman Fire area. However, effectiveness results will not be available for several years. Monitoring needs to be integral part of the postfire emergency rehabilitation treatment and evaluation.

References

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

Anderson 1974. H. W. 1974 (Pub1976). Fire effects on water supply, floods and sedimentation. In: Proceedings, annual tall timbers fire ecology conference; 1974 October 16-17; Tallahassee, FL: Tall Timber Research Station. 14: 249-260.

Arkell, R.E.; F. Richards. 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, N.C.

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

Barro, Susan C.; Conard, Susan G. 1987. Use of ryegrass seeding as an emergency revegetation measure in chaparral ecosystems. Gen. Tech. Rep. PSW-102. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.12 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.

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.

Beyers, Jan L.; Conard, Susan G.; Wakeman, Carla D. 1994. Impacts of an introduced grass, seeded for erosion control, on postfire community composition and species diversity in southern California chaparral. In: Proceedings of the 12th international conference on fire and forest meteorology, 1993 October 26-28; Jekyll Island, GA. Bethesda, MD: Society of American Foresters: 594-601.

Beyers, Jan L.; Wakeman, Carla D.; Wohlgemuth, Peter M.; Conard, Susan G. 1998a. Effects of postfire grass seeding on native vegetation in southern California chaparral. In: Proceedings, 19th annual forest vegetation management conference: wildfire rehabilitation, 1998 January 20-22; Redding, CA: Forest Vegetation Management Conference: 52-64.

Beyers, Jan L.; Wohlgemuth, Peter M.; Wakeman, Carla D.; Conard, Susan G. 1998b. Ryegrass seeding for post-fire erosion control in chaparral – does it work? Fire Management Notes 58: 30-34.

Biswell, H. H.; Schulz, A. M. 1965. Surface runoff and erosion as related to prescribed burning. Journal of Forestry. 55:372-373.

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.

Boyd, Anne; McKay, Mary; Dailey, Scott. 1995. Field observations on the Cleveland Fire, 1995 January 10; Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Eldorado National Forest, CA. 2 p.

Brooks, K. N.; Ffolliott, P. F.; Gregorsen, H. M.; DeBano, L. F. 1997. Hydrology and management of watersheds. Ames, IA: Iowa State University Press. 392 p.

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, G.S.; Jungbaurer, J. D., Jr.; Bristow, K. L.; Hungerford, R. D. 1995. Soil temperature and water content beneath a surface fire. Soil Cience. 159(6): 363-374.

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.

Croft, A. R.; Marston, Richard B. 1950. Summer rainfall characteristics in northern Utah. Transactions, American Geophysical Union 31(1): 83-95.

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

DeBano, L. F. 2000. The role of fire and soil heating on water repellency in wildland environments: a review, Journal of Hydrology 231-232: 195-206.

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.

DeGraff, J.V. 1982. Final evaluation of felled trees as a sediment retaining measure, Rock Creek Fire, Kings RD, Sierra National Forest, Fresno, CA. U.S. Department of Agriculture, Forest Service Special Report, Sierra National Forest, 15 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]

Farmer, E. E.; Van Haveren, B. P. 1971. Soil erosion by overland flow and raindrop splash on three mountain soils. Gen. Tech. Rep. INT-100. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

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.

Flanagan, S. A.; Furniss, M. J. 1997. Field indicators of inlet controlled road stream crossing capacity. No. 9777 1808-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology Center. 5 p.

Furniss, Michael J.; Ledwith, Tyler, S.; Love, Michael A.; McFadin, Bryan C. Flanagan, Sam A.1998. Response of road-stream crossings to large flood events in Washington, Oregon, and Northern California. San Dimas, CA: U.S. Department of Agriculture, Forest Service, Technology and Development Program, 9877 1806-San Dimas Technology Development Center. 14 p.

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

Green, Pat. 1990. 1989 soil monitoring report, Green Creek Point fire, Clearwater Ranger District. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Nez Perce National Forest, ID. 4 p.

Griffith, Robert W. 1989. Memo, silt fence monitoring. Unpublished report on file at: U.S. Department of Agriculture Forest Service, Stanislaus National Forest, CA. 4 p.

Hartford, R. A.; Frandsen, W. H. 1992. When it's hot, it's hot—or maybe it's not (surface flaming may not portend extensive soil heating). International Journal of Wildland Fire 2: 139-144.

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.

Hoyt, W. G.; Troxell, H. 1934. Forests and streamflow. Trans. Am. Soc. Civil Engineers. 99:1.

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.

Inbar, M; Tamir, M; Wittenberg, L. 1998. Runoff and erosion processes after a forest fire in Mount Carmel, a Mediterranean area. Geomorphology, 24: 17-33.

Kidd, Jerry L.; Rittenhouse, Dave. 1997. Evaluation of storm effects on Eight Street Fire Rehabilitation. Unpublished report on file at: U.S. Department of Interior, Bureau of Land Management, Boise, ID. 8 p.

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

Krammes, J. S.; Rice, R. M. 1963. Effect of fire on the San Dimas Experimental Forest: Proceedings: Arizona watershed symposium, 7th Annual Meeting; [date unknown] Phoenix, Arizona publisher unknown]: 31-34.

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

MacDonald, L.H. 2000. Evaluating and managing cumulative effects: process and constraints, Environmental Management, 26(3): 299-315.

MacDonald, L.H. 2002. [Personal communication]. October 20. Fort Collins, CO: Colorado State University, Department of Earth Resources.

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.

MacDonald, L.H.; Sampson, R.;Brady, D.; Juarros, L.; Martin, D. 2000. Predicing postfire erosion and sedimentation risk on a landscape scale: a case study from Colorado, Journal of Sustainable Foresty, 11(1/2): 57-87.

MacDonald, L.H.; Smart, A.W.; Wissmar, R.C. 1991. Monitoring guidelines to evaluate the effects of forestry activities on streams in the Pacific Northwest and Alaska. 910/9-91-001, Region 10, US Environmental Protection Agency, Seattle, WA, 166 p.

Maloney, P. Cavan; Thornton, John L. 1995. Implementation and effectiveness monitoring of best management practices and soil and water protection measures within the Foothills Fire salvage logging area 1992-1995. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Boise National Forest, ID. 51 p.

McCammon, B. P.; Hughes, D. 1980. Fire rehab in the Bend municipal watershed. In: Proceedings of the 1980 watershed management symposium, 1980 July 21-23; Boise, ID: New York: American Society of Civil Engineers: 252-259.

McNabb, D. H.; Swanson, F. J. 1990. Effects of fire on soil erosion. In: Walstad, J. D.; Radosevich, S. R.; Sandberg, D. V. (eds.). Natural and prescribed fire in Pacific northwest forests. Corvallis, OR: Oregon State University Press, p. 159-176.

Meeuwig, R. O. 1971. Soil stability on high-elevation rangeland in the intermountain area. Research Paper INT-94. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 10 p.

Megahan, W. F. 1986. Recent studies on erosion and its control on forest lands in the United States. In: Richard, F. (ed.). Range basin sediment delivery: Proceedings; 1986 August; Albuquerque, NM: IAHS Pub. 159, Wallingford, Oxon, United Kingdom: 178-189.

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.

Montgomery, D.R.; Dietrich, W.E., 1994. A physically based model for the topographic control on shallow landsliding, Water Resources Research, 30(4): 1153-1171.

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

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. Postwildfire peak flood flows: Causes and effects. In: Proceedings Society of American Foresters 2000 National Convention; 2000 November 16-20; Washington, D.C., Society of American Foresters, Bethesda, MD, p. 459-463.

Neary, D. G.; Hornbeck, J. W. 1994. Chapter 4: Impacts of harvesting and associated practices on off-site environmental quality. In: Dyck, W. J.; Cole, D. W.; Comerford, N. B., eds. Impacts of forest harvesting on long-term site productivity. London: Chapman & Hall, p. 81-118.

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.

Parsons, Annette. 1994. Field notes from burn rehab and soil erosion monitoring day trip to observe treatments at 2 years postfire. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Eldorado National Forest, CA. 5 p.

Pyne, S J.; Andrews, P. L.; Laven, R. D. 1996. Introduction to wildland fire. New York: John Wiley & Sons. 769 p.

Reid, L. M. 1993. Research and cumulative watershed effects. Gen. Tech. Rep. PSW-GTR-141. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 118 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. 2002. [Personal communication]. October 15. Moscow, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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, 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.

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

Rosgen, D. L. 1996. Applied river morphology. Pagosa Springs, CO: Wildland Hydrology. 364 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.

Sinclair, J. D.; Hamilton, E. L. 1955. Streamflow reactions to a fire-damaged watershed. In: Proceedings of the Hydraulic Division. American Society of Civil Engineering, New York.

U.S. Department of Agriculture, Forest Service. 2000. Environmental assessment for the Upper South Platte watershed protection and restoration project, USDA Forest Service, 2000 August.

U.S. Department of Agriculture, Forest Service. 2002. 7/5/02 Hayman Fire—burned area report. Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Pike and San Isabel National Forest, Pueblo, CO. 7 p.

Wagenbrenner, J. W.; MacDonald, L. H.; Rough, D. T. M. 2002. Effectiveness of seeding, mulching, and coutour felling after wildfires in the Colorado Front Range. Poster paper presented at 2002 Geological Society of America Annual Meeting: Science at the highest level, 2002 October 27-30; Denver, CO.

Wohlgemuth, Peter M.; Beyers, Jan L.; Wakeman, Carla D.; Conard, Susan G. 1998. Effects of fire and grass seeding on soil erosion in southern California chaparral. In: Proceedings, 19th annual forest vegetation management conference: wildfire rehabilitation, 1998 January 20-22; Redding, CA. Forest Vegetation Management Conference: 41-51.