Post-Wildfire Erosion in the Southwest: Causes and Control

Daniel G. Neary, Gerald J. Gottfried,[1]
Leonard F. DeBano, and Peter F. Ffolliott[2]

Wildfire is a major disturbance in woodlands and forests of the Southwest. It exerts major influences on the vegetation, fauna, soils, hydrology, and erosional processes of watersheds. One of the adverse impacts of wildfires in southwestern forests and woodlands is a potential for large increases in erosion rates. Natural erosion rates of <0.1 to 5.5 Mg/ha can suddenly climb to the 204 to 370 Mg/ha range under the right conditions (DeBano et al. 1997). High fire severity, steep slopes, combustion of surface organic matter (vegetative ground cover and litter), development of water repellency in the soil, shallow soils, the occurrence of high-intensity rainfall immediately after the spring fire season, and mountainous terrain are the main factors leading to increased erosion rates. Because of these factors, the Southwest has the greatest potential for post-wildfire sediment yield increases in North America (Swanson 1981). More than 70 percent of long-term sediment yield in southwestern chaparral can be produced by wildfires.

Post-fire burned area emergency rehabilitation analyses (LaFayette 1998) often recommend erosion control practices such as seeding with native grasses and forbs, contour ditching, and contour felling of fire-killed trees. Although these techniques can reduce surface and rill erosion over a long time period, they have variable effects on immediate post-fire surface erosion and can have little effect on the gully development, debris avalanches, and channel destabilization processes that produce the largest post-fire sediment yields. The objectives of this paper are to (a) examine the causes of post-wildfire erosion, (b) discuss management controls that can mitigate sediment movement off of burned areas and into streams or ephemeral channels, and (c) provide some recent examples of post-fire erosion that occurred irrespective of erosion control mitigation.

Erosion Processes

Watershed condition describes the ability of a watershed system to receive and process precipitation without ecosystem degradation. Organic material on the soil surface and vegetative ground cover moderate the impact of falling raindrops, allowing water to infiltrate into the soil, thereby minimizing overland flows. Loss of litter and vegetation by burning or other disturbances will result in degradation of hydrologic functions (Neary 1996). With Agood@ soil hydrologic condition, precipitation infiltrates into the soil, and baseflows are sustained between storms. Rainfall that infiltrates into the soil usually does not contribute to erosion because it does not flow over the surface where it can detach and transport sediments. If intense wildfires produce severe changes in the amounts of litter and vegetation on a watershed, infiltration rates are reduced and overland flow increases over the soil surface, producing excessive erosion (Table 1). The result can be little or no baseflow between storms, and considerable erosion during stormflows (Neary 1996).

The erosion process involves three separate components that are a function of sediment size and transport medium (water or air) velocity: detachment, transport, and deposition. Erosion occurs when soil particles or channel sediments are exposed to falling raindrops, flowing water, or air and velocities that are sufficient to detach and transport these sediments. Table 2 gives a break-

Table 1. Summary of Soil Conditions and Typical Infiltration Rates.

Surface Conditions	Infiltration (mm/hr)	
Complete litter cover	>160	Very rapid
Vegetation cover, little litter	5–50	Slow to moderate
Bare soil	0–25	Very to moderately slow
Water repellent soil	0–10	Very slow to none

Source: Neary et al. 1998

[1]USDA Forest Serv., Rocky Mtn. Research Station, Flagstaff, AZ
[2]University of Arizona, Tucson

Table 2. Sediment Sizes, and Detachment and Deposition Velocities.

Sediment	Size Class Diameter (mm)	Detachment Velocity (cm/sec)	Deposition Velocity (cm/sec)
Boulders	>1000–256	>190	<120
Cobble	256–64	>150	<80
Gravel	64–2	>35	<15
Sand	2–0.17	>17	<1.5
Silt	0.17–0.004	>250	<0.1
Clay	0.004–0.0001		

Source: Neary et al. 1998

down of sediment classes and detachment-transport-deposition velocities for flowing water. Clay-sized sediment particles have very high detachment velocities because of the stability of the soil aggregates that they form (Table 2). Silt- and clay-sized sediments in suspension in water are the most difficult to control because of the extremely low velocities and long time frames at which they settle out of the water column.

Erosion is a natural process occurring on all landscapes at different rates and scales depending on soils, geology, topography, vegetation, and climate. Some examples of natural rates of erosion in the United States are shown in Table 3. Geologic erosion rates were calculated on large drainage basins, so they are higher than those listed for forests; the latter data from forests come from much smaller watershed experiments. Natural erosion rates increase as annual precipitation increases, peaking in semi-arid zones that are transitions from desert to grassland (Hudson 1981).

Table 3. Examples of Natural Erosion Rates in the Continental USA.

WS Condition	Sediment Loss Rate First Yr (mg/ha)	Reference
USA:		
Geologic erosion		Schumm &Harvey 1982
Natural, lower limit	0.580	
Natural, upper limit	15.000	
East USA:		
Forests, baseline lower	0.110	Patric 1976
Forests, baseline upper	0.220	
West USA:		
Forest, baseline lower	0.001	Biswell & Schultz 1965
Forest, baseline high	5.530	DeByle & Packer 1972

The amount of vegetative and litter surface cover remaining after a fire affects infiltration, runoff, and erosion (Table 4). Litter charring usually does not result in significant erosion. After the litter and underlying duff are consumed, bare soil is exposed, raindrop impact occurs, and significant sheet, rill, and gully erosion can occur. If a fire is severe enough to produce wettability problems, then mass wasting (the most severe form of post-fire erosion) is a possibility on steep terrain. The amount and severity of erosion is a function of the duration, amount, intensity, and timing of precipitation as well as the season, timing, and severity of the fire events. Generally speaking, erosion rates are the highest the first year after a fire and where 100 percent of a watershed has burned (Figure 1). Post-fire erosion ratios (PFERs)

Table 4. Soil Surface Conditions and Relative Infiltration, Runoff, and Erosion.

Soil & Litter Condition	Infiltration	Runoff	Erosion	Watershed Condition
Litter charred	High	Low	Low	Good
Litter consumed	Medium	Medium	Medium	Fair
Bare soil	Low	High	High	Poor
Water repellent	Very low	Very high	Severe	Very poor

Source: Neary et al. 1998

are the simple ratios of average pre-fire erosion rates (Mg/ha/yr) to post-fire rates for the first, second, third, etc. years after a fire. The value of the PFER is a function of fire severity, slope steepness, soil characteristics, degree of surface organic matter combustion, extent of development of water repellency, amount of shallow soils, and the occurrence and duration of high-intensity rainfall. The timing of the return of the PFER to normal (value of 1) is also a function of these same factors and can range from a year to decades. Reported values for the first-year PFER range from 2 in the Coastal Plain of the southeastern USA (Ferguson 1957) to 370,000 in Arizona chaparral (Hendricks and Johnson 1944).

The major erosion processes are sheet erosion, rill erosion, gully erosion, mass wasting, and channel destabilization. Sheet erosion is a gradual removal of the soil surface by transport during surface runoff. Rill erosion involves the development of small incisions in the soil surface. As rills

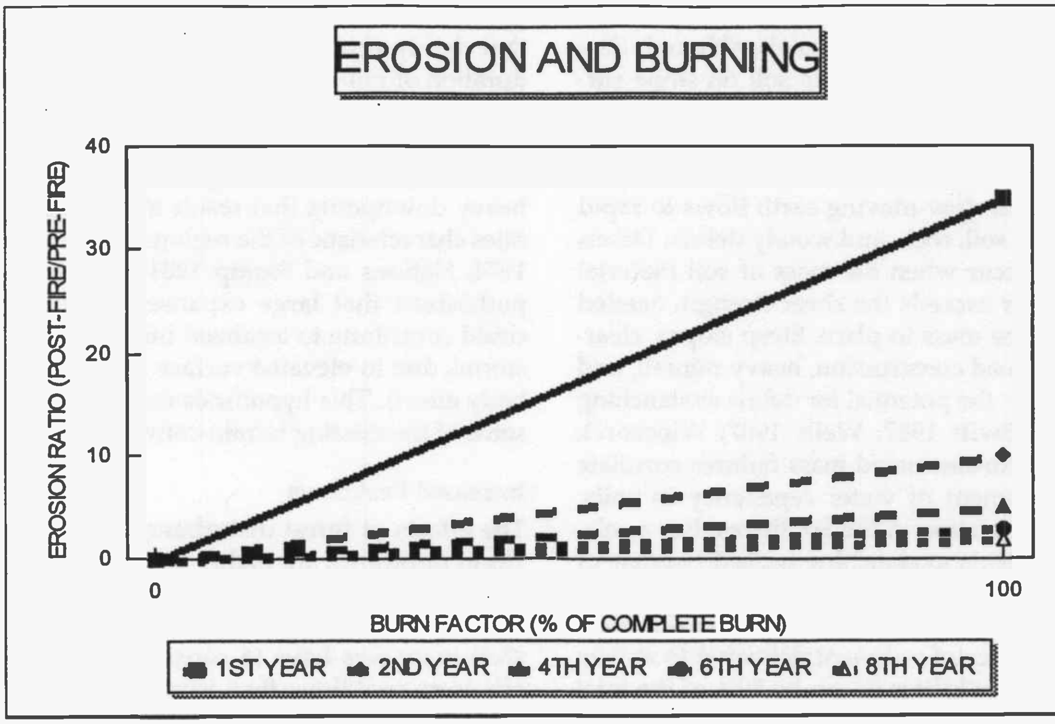

Figure 1. Relative erosion rates 1, 2, 4, 6, and 8 years after burning for a hypothetical watershed.

expand they become deep gullies. In mass wasting, large sections of hillslope can fail, producing slow to very rapid movement of tens or thousands of cubic meters of soil downslope. Stream channels can destabilize and downcut with increased stormflows, transporting large amounts of channel sediments during channel degradation.

Sheet and Rill Erosion

During sheet erosion, fine soil particles and residual ash on soil surfaces erode relatively uniformly. This results in a gradual removal of the A horizon and a lowering of the surfaces. Sheet erosion degrades soil condition and ultimately reduces watershed functions and ecosystem sustainability (Neary and Michael 1997). As erosion progresses, rills (small channels) develop. When rill erosion begins, small, linear, rectangular or V-shaped channels cut deeper into the surface of a slope. Eventually rills progress to a size where they are classified as gullies. Functioning of the soil system can be slightly to moderately impaired during sheet erosion and rill development.

Gully Development

If rills continue to deepen and widen, they develop into gullies. These erosion features are deep, large, rectangular to V-shaped channels that cut into a slope. Gullies can erode downwards through the soil and into underlying parent material. Incision of gullies moves large amounts of sediments on to lower slopes or steam channels. Additional downcutting of rectangular cross-sectioned, F-type channels (Rosgen 1996) created by gullies, dry gravel of the perpendicular banks, and eventual lowering of the angle of repose results in large amounts of sediment yield over a long period of time. This cause of erosion is difficult to predict, and controls are restricted to after-the-fact when much of the sediment movement has already occurred. Gullies severely degrade site productivity and ecological function, and are major sediment sources because of their rapid cutting rates, and creation of steep, erodible, side walls. Control of sediment and restoration of gullies is very expensive and requires periodic and costly maintenance.

Mass Wasting

Mass wasting includes slope creep, rotational slumps, and debris avalanches. Slope creep is a slow process that does not deliver large amounts of sediment to stream channels in the time periods normally considered in watershed management. Rotational slumps involve a failure and rotation of a slope but normally do not move any significant distance. Slumps are only major problems when they occur close to stream channels, although they also expose large areas of bare soil on slope surfaces. Debris avalanches are the largest, most dramatic, and main form of mass wasting; they deliver large amounts of sediment to streams, and can range from slow-moving earth flows to rapid avalanches of soil, rock, and woody debris. Debris avalanches occur when the mass of soil material and soil water exceeds the sheer strength needed to maintain the mass in place. Steep slopes, clearcut logging, road construction, heavy rainfall, and fires aggravate the potential for debris avalanching (Neary and Swift 1987; Wells 1987; Wieczorek 1987). Most fire-associated mass failures correlate with development of water repellency in soils. Chaparral vegetation in the Southwest has a relatively high debris avalanching hazard because of the tendency for development of water repellency in soils of these ecosystems. Debris avalanches are the largest source of sediment delivered to stream channels after wildfires (it can be 50% of the total post-fire sediment yield in some ecoregions; Swanson 1981).

Channel Destabilization

Increased streamflows, particularly peakflows, following wildfire can result in channel downcutting and the downstream transport of additional and larger sediments (Neary 1996). Peakflows are the hydrologic events that produce the most significant changes in channel morphology and sedimentation. Small increases in stream velocity during peakflows can exceed detachment velocity thresholds for sediment classes (Table 2), and can result in significant transport of bedload material.

Erosion Causes

High Fire Severity

Fire severity is a key factor in determining the amount of post-fire erosional loss of soil. Low and moderate severity fires leave most or some of the O horizon (litter and duff) on the soil surface. Vegetative ground cover and litter mitigate the force of raindrop impact, ensuring that much of the rainwater infiltrates into the soil. Surface runoff is the predominant mechanism of rainfall flow when the O horizon is completely burned off. Erosion is then greatly enhanced.

Precipitation Patterns and Intensities

The amount of post-fire erosion is a result of many factors associated with precipitation that, in the Southwest, results in high, post-fire erosion rates (Swanson 1981; Neary 1996). Rainfall is the process that drives erosion. The amount, intensity, and duration of rain are important properties that contribute to erosion severity. Monsoons that enter the Southwest immediately after the May-June fire season interact with steep terrain to trigger the heavy downpours that result in the high erosion rates characteristic of the region (Green and Sellers 1974; Nations and Stump 1981). It has been hypothesized that large expanses of burned area could contribute to localized buildup of thunderstorms due to elevated surface heating (the black body effect). This hypothesis could be tested with some of the existing terrain-convection models.

Increased Peakflows

The effects of forest disturbances such as fire on storm peakflows are highly variable and complex (Neary 1996). These disturbances can produce some of the most profound impacts that watershed managers have to consider. Fire has larger effects on peakflows than harvesting (Anderson et al. 1976; Bosch and Hewlett 1982; Neary and Hornbeck 1994). A wildfire in Arizona increased summer peakflows by 500–1500 percent, but had no effect on winter peakflows (Anderson et al. 1976). Another wildfire in Arizona produced a peakflow 58 times greater than an unburned watershed during record autumn rainfalls. Watersheds in the Southwest are prone to these high peakflow responses due to climatic and soil conditions. Another concern is the timing of stormflows or response time. Burned watersheds respond to rainfall faster, producing more flash floods. Hydrophobic soils, bare ground, and vegetative cover loss will cause flood peaks to arrive faster and at higher levels. Flood warning times are reduced by flashy flow, and higher flood levels can be devastating to property and human life. The Southwest is not only vulnerable to large changes in peakflow response time and volume, but also recovery times are typically slower than other ecoregions and can range from years to many decades.

Steep Slopes

Slope is also a major factor in determining the amount of erosion, because it directly affects the velocity and hence the erosive power of water. Erosion from two watersheds of the Southwest Plateau Dry Steppe ecoregion of Texas was significantly influenced by slope during successive years. A watershed with 45–50 percent slopes produced sediment at a rate 8–10 times greater than one with slopes of 15–20 percent (Wright et al. 1976).

Combustion of Organic Matter and Development of Water Repellency

After particularly severe wildfires that consume all of the vegetative ground cover and litter on the surface, the ash-covered soil is left exposed to raindrop impact. In some soil and vegetation associations, heat from combustion drives volatile organic byproducts into the soil, where they eventually condense and form a hydrophobic or non-wettable layer. Subsequent rainfall infiltrates until it reaches this layer and is then forced to move laterally. This results in rill and gully formation or slope failure (DeBano et al. 1998; Wells 1987).

Shallow Soils, Compacted Soils, and Roads

Overland flow occurs when rain intensity or snowmelt rate exceed infiltration capacity. It typically occurs on shallow soils, compacted soils, rock, and roads. Overland flow that is 1 percent of rainfall in undisturbed forests can increase to 15–40 percent after fires. Fire-related wettability problems are a big contributor to this response. However, roads created during fire suppression activities or soils compacted by heavy machinery traffic can also exacerbate the problem if road densities are high, intense fire temperatures affect much of the soil profile, and erosion removes much of the developed soil profile. Shallow soils are particularly sensitive to fire-induced changes in their hydrologic condition. Thermal degradation of physical and chemical properties of soils can produce significant surface runoff problems after severe fires.

Erosion Control

Several treatments are used to control erosion after wildfires (Miles 1998). Hillslope treatments are generally used to control sheet and rill erosion, and to prevent gully development. Channel treatments are recommended to either stabilize gullies or prevent channel destabilization due to increased post-fire peakflows (DeBano et al. 1998). Road treatments are implemented to reduce erosion associated with temporary fire suppression roads, dozer lines, fire equipment–impacted permanent roads, or water-handling structures associated with roads that could be potentially affected by increased post-fire peakflows.

Hillslope treatments to control erosion include mulching, seeding, soil and sediment trapping, tilling, and laying erosion control mats (Table 5). Mulching is done to provide instant ground cover for sensitive areas. Treatments include hand, contour strip, and machine mulching. Seeding with grass and herbaceous plants is the most common technique. Because of problems with exotic plant persistence, displacement of native species, and spread to adjacent areas, much of the emphasis in recent years has been to reseed with native plants. Seeding is used to reduce surface erosion by providing ground cover, but it has a delay factor

Table 5. Hillslope Erosion Control Treatments and Comments (Adapted from Miles 1998).

Treatment	Type	Comments
Mulching	Hand	100% cover, labor intensive, expensive ($1,850–$5,500/ha)
	Contour strip	50% cover, cost <50% of hand, faster production rate
	Machine	Limited to road access areas and firelines, high production rate
Seeding	Aerial	Very high production rate, low cost, quick implementation
	Hand	Best suited to remote or sensitive areas <10 ha in size
	Hydromulch	Limited to areas above and below roads, production rate >hand
Soil trapping	Contour felling logs	70-250 logs/ha, difficult to do correctly, safety hazards
	Straw wattles	Easy to apply, very effective, lasts 2-4 years, expensive, fire hazard
	Sand bags	Labor intensive, infrequent use, bag material persistent
	Slash lopping and scattering	Production rate slow, ground contact difficult, safety hazards
	Trenching	Hand or machine, cost variable, labor intensive, hydrophobic soils
	Silt fences	Used where sediment movement significant, installation critical
Tilling	Subsoiling or ripping	Difficult in heavy brush or rocky soils, production rate slow
	Disking	Good for hydrophobic soils, slope limitations
Erosion mats	Fiber mats	100% cover, effective, $25,000/ha
	Jute netting	<100% cover, effective, high cost

due to the need for plants to germinate and grow. Seeding can be done by air, hand, or hydromulching methods. Soil particles can be trapped on hillslopes by contour-felled logs, straw bales, sand bags, slash deposits, contour trenching, or silt fences. Machine tilling can be done on the contour of gentle slopes to break up hydrophobic soil conditions. Fiber mats or jute netting can be laid on the surface of sensitive or high-value areas to provide instant ground cover.

Gullies are more difficult to deal with, and require more expensive control structures. Rock or log check dams are frequently used to stabilize gullies; these usually are not preventative measures, and are used after gullies or channel cutting starts. Gully or channel stabilization treatments include grade stabilizers, check dams, bank and channel armoring, stream bank shaping and revegetation, channel organic debris clearing, and debris basins (Table 6). These techniques are usually more expensive than hillslope treatments, although they are typically confined to smaller areas. Grade stabilizers are used to reduce downcutting by establishing grade control and reducing water velocity. Rock and logs can be used for these structures. Check dams made of rock, logs, straw bales, or straw wattles are used to trap sediment in ephemeral or small perennial channels. Bank armoring can be used to reduce the impacts of increased peakflows that accompany wildfires. Channel clearing can be done to remove excessive debris around bridge approaches, but it is not recommended for extensive use along stream courses. Debris basins are large constructed structures used to trap sediments over long periods of time; they are expensive to construct and require considerable engineering during construction and must be maintained frequently.

New roads constructed during fires, or existing ones that are frequently used by heavy equipment and fire engines, are another source of post-fire sediment. Temporary roads (including fire lines and dozer lines) used for fire suppression are usually closed out after supression activities have concluded. Ripping, water bar construction, and seeding are the main treatments for erosion control. Treatments for existing system roads include culvert upgrades, broad-based dips, trash racks, energy dissipators, gravel additions to road surfaces, and storm patrols to make sure culverts do not block up and fail during significant rainfall events (Table 7).

1996 Fire Season Examples

Two examples of post-wildfire erosion occurred in the Southwest during and immediately following the 1996 fire season. In both cases, accelerated erosion followed the onset of heavy monsoon rains. Erosion control carried out in the first example was ineffective due to the erosion mechanism and storm event timing.

White Springs Fire

One of the first of many 1996 wildfires in Arizona occurred in April at White Springs on the White Mountain Apache Reservation. Although the burned area received rehabilitation treatments (grass seeding, contour felling of small snags, fireline and dozer trail restoration, etc.), gully formation occurred on two watersheds during heavy

Table 6. Channel Erosion Control Treatments and Comments (Adapted from Miles 1998).

Treatment	Type	Comments
Grade stabilizers	Rock	Ephemeral or small channels with lot of rock, organic debris needed
	Logs	Ephemeral or small channels, down wood present (30–50 cm diameter)
Check dams	Rock fence	Replaces woody debris, design for keying, spillway, energy dissipation
	Logs	Log size 30-45 cm diameter, stacked, same design features as rock fence
	Straw bales	Low gradients with no rock and wood, simple, quick construction
	Straw wattle dams	Similar to straw bales, lifetime of 2-4 years
Bank/channel armoring	Rock-wire gabions	Reduces impacts of high peak flows, smaller rock, high construction costs
	Boulders	Reduces impacts of high peak flows, large rock needed
	Reshaping/revegetation	Improves flow, eliminates vertical banks, stabilizes soil and sediment
Channel clearing	Woody debris removal	Prevents woody debris from building up above bridges and culverts
	Excess sediment removal	Increases channel flow handling capacity
Debris basins	Constructed structures	Expensive, require qualified engineer design, high maintenance cost, high storage capacity

Table 7. Road Erosion Control Treatments and Comments (Adapted from Miles 1998).

Treatment	Type	Comments
Culvert upgrades	Size	Adequate design to handle increased streamflow or debris load
	Frequency	Decrease flow in inside ditches
	Riser pipes	Detain sediment
Broad-based dips		Divert water off road surfaces, backup for plugged culverts
Cable trash racks		Trap woody debris before culverts become plugged
Energy dissipators		Placed below culvert outlets to reduce the erosive energy of outflow
Road surface		Rock surfacing to armor against raindrop impact, and trap sediment
Storm patrols		Ensures that existing culverts do not become blocked and fail during storms

monsoon rains in July. The major gully on the White Springs Fire incised a channel about 5 m wide and 2 m deep into an alluvial fan containing an old, stabilized gully. The freshly eroded area traversed the alluvial fan for about 300 m in an upslope direction to a point where gully formation was halted by a bedrock outcrop. Intense rainfall apparently set off this erosional episode. The burned area rehabilitation treatments, although prescribed and applied according to all acceptable standards and quality, were insufficient to prevent the erosion, as the grass seed had not yet germinated and the contour felling was conducted on a limited area of the watershed and was incapable of retarding the flows that incised the new gully.

Hochderffer Fire

The Hochderffer Fire in June, 1996, burned 6400 ha on cinder cones northwest of the San Francisco Peaks on the Coconino National Forest. The wildfire produced a spectrum of severities, with some of the highest on the Hochderffer Hills where the fire originated. The emergency rehabilitation treatment (native grass seeding) was for road repair, fireline restoration, and stabilization of about 809 ha of steep slopes. Other treatments were not recommended because no streams or riparian areas existed in or adjacent to the burned area. An intense thunderstorm 2–3 weeks after the fire produced extensive sheet erosion and some gully formation. One gully incised 3–4 m deep and 4–5 m wide into an old alluvial fan and transported fresh sediments 300–400 m downslope. No streams were impacted by sediment deposition after the July, 1996, erosion event because the alluvial fan dissipates onto the south side of the streamless Kendrick Park along the north flank of the fire boundary.

In the Flagstaff area, the lowest precipitation month is June with an average of 10 mm (the lower curve in Figure 2; Sellers and Hill 1972; Staudenmeier 1998). It is followed by the highest precipitation month (July, lower curve, 71 mm average rainfall). However, maximum rainfall for July has been as high as 193 mm (upper curve). So the potential exists for considerable watershed response to post-fire rainfall. Unfortunately, no rain gages were located in the Hochderffer Hills area. Doppler Radar data are available but have not been analyzed. The existing intensity data for the Flagstaff weather record illustrate the characteristics of rainfall intensities for the area. Precipitation durations for the period of record from 5 to 1440 minutes (24 hours) and their associated amounts are shown for storms with 10 and 100 year return periods (Figure 3). The maximum recorded 24-hour precipitation in July (65 mm) is the level line across the center of the graph. If the thunderstorm that produced the Hochderffer Hills gully blowout was close to the maximum, it would take a 10-year event 12 hours (5.4 mm/hr) and a 100-year event 3 hours (21.7 mm/hr) to reach the 65 mm amount. Although rainfall intensities and durations required to initiate debris flows and large gully formation in the Flagstaff area are not known, intensities characteristic of the 100-year event are well within the range of those known to produce significant hillslope erosion (Wells 1987).

Summary and Conclusions

Over the long term, watersheds in the Southwest produce significant amounts of sediment from severe wildfires. We have briefly looked at some of the causes and controls of erosion after wildfires. Many different and effective treatments are available for emergency rehabilitation of burned areas. Although burned area emergency rehabilitation is often conducted after wildfires, erosion and sedimentation immediately after a fire cannot be completely controlled. Emergency rehabilitation techniques are usually successful in long-term site stabilization and erosion control.

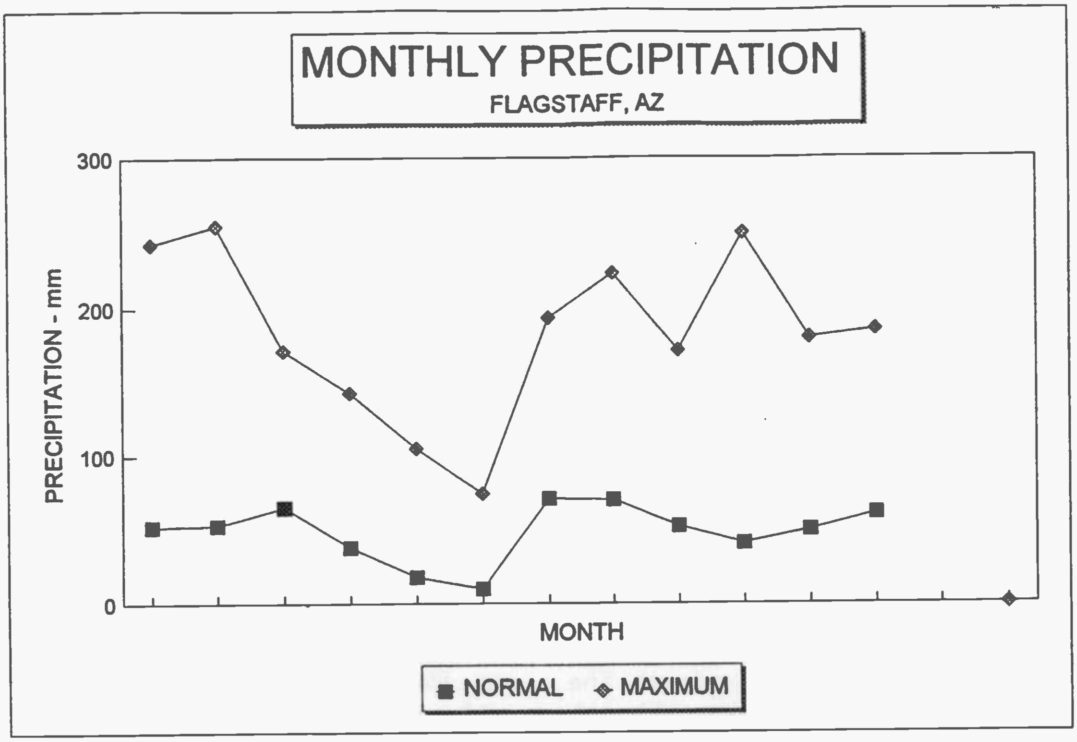

Figure 2. Average and maximum monthly precipitation, Flagstaff, Arizona.

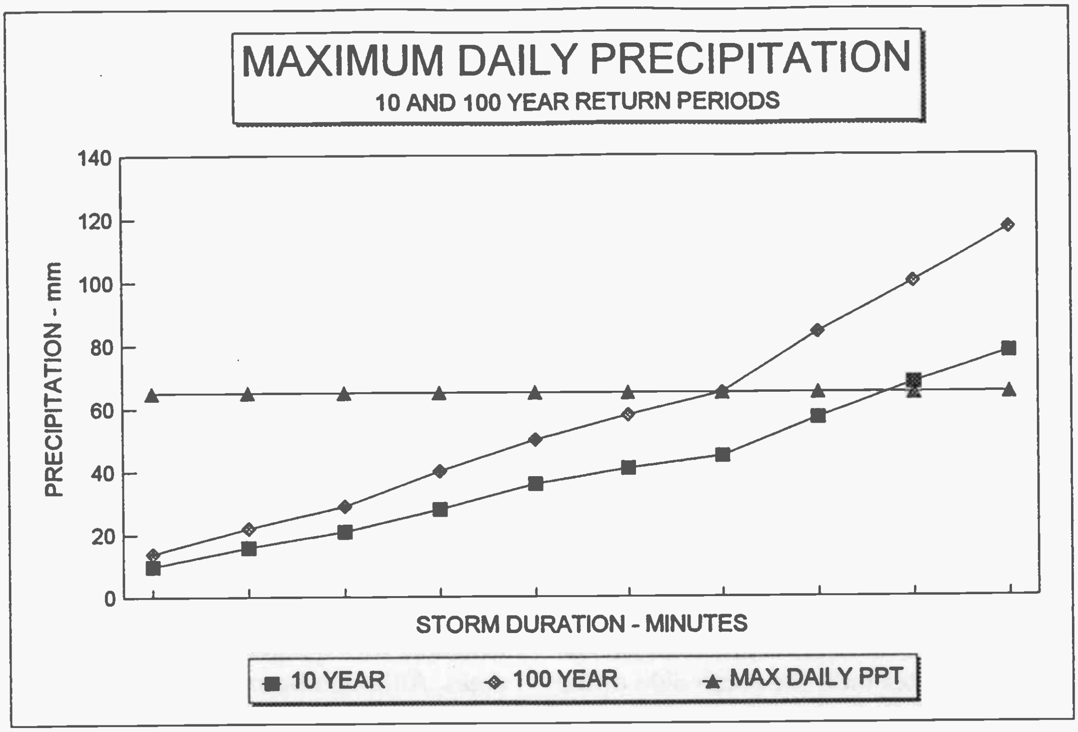

Figure 3. Maximum daily precipitation and durations for 10- and 100-year events, Flagstaff, Arizona.

References Cited

Anderson, H. W., M. D. Hoover, and K. G. Reinhart. 1976. Forests and water: Effects of forest management on floods, sedimentation, and water supply. USDA Forest Service General Technical Report PSW-18, 115 pp.

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

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55: 3–23.

DeBano, L. F., M. B. Baker Jr., P. F. Ffolliott, and D. G. Neary. 1997. Fire severity and watershed resource responses in the Southwest. Hydrology and Water Resources in Arizona and the Southwest 26: 39–44.

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 1998. Fire's effects on ecosystems. John Wiley & Sons, New York. 333 pp.

DeByle, N. V. and P. E. Packer. 1972. Plant nutrient losses in overland flow from burned forest clearcuts. Pages 296–307 in Watersheds in Transition: Proceedings of a Symposium, American Water Resources Association and Colorado State University, Fort Collins.

Ferguson, E. R. 1957. Prescribed burning in shortleaf-loblolly pine on rolling uplands in east Texas. USDA Fire Control Notes 18: 130–132.

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

Hudson, N. W. 1981. Soil conservation. Cornell University Press, New York.

LaFayette, R. A. 1998. Burned area emergency rehabilitation: Authorities and policy. 86 pp. In Region 6 Burned Area Emergency Rehabilitation Manual, USDA Forest Service, San Francisco.

Miles, S. R. 1998. Listing of BAER treatments: Cost, risk, effectiveness, production rates, and applications. In Region 6 Burned Area Emergency Rehabilitation Manual, USDA Forest Service, San Francisco. 6 pp.

Nations, D. and E. Stump. 1981. Geology of Arizona. Kendall/Hunt, Dubuque, IA. 221 pp.

Neary, D. G. 1996. Effects of fire on water resources—A review. Hydrology and Water Resources in Arizona and the Southwest. 25: 45–53

Neary, D. G. and J. W. Hornbeck. 1994. Chapter 4: Impacts of harvesting and associated practices on off-site environmental quality. Pages 81–118 in W. J. Dyck, D. W. Cole, and N. B. Comerford (Eds.) Impacts of forest harvesting on long-term site productivity, Chapman & Hall, London. 371 pp.

Neary, D. G. and J. L. Michael. 1997. Herbicides—Protecting long-term sustainability and water quality in forest ecosystems. New Zealand Journal of Forestry Sciences 26: 241–264.

Neary, D. G. and L. W. Swift, Jr. 1987. Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian mountains. Pages 81–92 in J. E. Costa and G. F. Wieczorek (Eds.) Reviews in Engineering Geology Volume VII: Debris Flows/Avalanches: Processes, Recognition, and Mitigation. Geological Society of America, Boulder, CO. 239 pp.

Neary, D. G., L. F. DeBano, and R. Hungerford. 1998. Unit II-A/B: Soils, water, and aquatic ecology. Fire in Ecosystem Management, National Advanced Resource Technology Center, Marana, AZ, March 31–April 9, 1998. 74 pp.

Patric, J. H. 1976. Soil erosion in eastern forests. Journal of Forestry 74: 671–676.

Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, CO. 362 pp.

Schumm, S. A. and M. D. Harvey. 1982. Natural erosion in the USA. Pages 23–39 in B. L. Schmidt (Ed.) Determinants of Soil Loss Tolerance. Special Publication 45, American Society of Agronomy, Madison, WI.

Sellers, W. D. and R. H. Hill. 1972. Arizona Climate 1931–1972. University of Arizona Press, Tucson. 616 pp.

Swanson, F. J. 1981. Fire and geomorphic processes. Pages 410–420 in Mooney, H. (Ed.) Fire Regimes and Ecosystem Properties: Proceedings of the Conference. USDA Forest Service General Technical Report WO-26, Washington, D.C.

Wells, W. G. III. 1987. The effects of fire on the generation of debris flows in southern California. Pages 105–114 in J. E. Costa and G. F. Wieczorek (Eds.) Reviews in Engineering Geology Volume VII: Debris Flows/Avalanches: Processes, Recognition, and Mitigation. Geological Society of America, Boulder, CO, 239 pp.

Wieczorek, G. F. 1987. Effect of rainfall and duration on debris flows in central Santa Cruz mountains. Pages 93–104 in J. E. Costa and G. F. Wieczorek (Eds.) Reviews in Engineering Geology Volume VII: Debris Flows/Avalanches: Processes, Recognition, and Mitigation. Geological Society of America, Boulder, CO, 239 pp.

Wright, H. A., F. M. Churchill, and W. C. Stevens. 1976. Effects of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas. Journal of Range Management 29: 294–298.