FLOODS AND SEDIMENT YIELDS FROM RECENT WILDFIRES IN ARIZONA

Daniel G. Neary, Project Leader, USDA Forest Service, Rocky Mountain Research Station, Flagstaff, Arizona, dneary@fs.fed.us; Gerald J. Gottfried, Research Forester, USDA Forest Service, Rocky Mountain Research Station, Phoenix, Arizona, ggottfried@fs.fed.us; Jan L. Beyers, Research Plant Ecologist, USDA Forest Service, Pacific Southwest Research Station, Riverside, California, jbeyers@fs.fed.us; Peter F. Ffolliott, Professor, School of Natural Resources, University of Arizona, Tucson, Arizona, ffolpete@ag.arizona

Abstract: Large area, high severity wildfires have become common in the Southwest since the mid-1990s due to drought, excessive woody fuel buildups, exotic grass invasions, and increasing ignition sources. These fires have alter watershed conditions, resulting in greater storm peakflows and sediment losses. This paper examines information gathered from three Arizona wildfires that burned ponderosa pine or mixed-conifer forests. Previous wildfires produced flood peakflows between 5 and 407 times greater than pre-wildfire peakflows. Erosion rates have ranged from 4.2 to 370 Mg/ha/yr. The Coon Creek Fire burned 3,887 ha in April, 2000. The wildfire was classified as uniform high severity in the mixed-conifer Middle Fork drainage of Workman Creek. A rainfall burst of 66 mm in 15 minutes during a monsoon thunderstorm produced a weir-overtopping peakflow (57.4 m^3/s) of more than seven times the previous 40-year record peakflow (8.2 m^3/s). Two additional peakflows that overtopped the main weir occurred in 2001, and were estimated at 11.9 m^3/s. Sediment yield during the first storm could not be calculated because of the size of the flood flow. After the first flood flow in 2000, sediment yields returned to normal (39.3 m^3/yr). The Rodeo-Chediski Fire of 2002 burned 187,290 ha in the headwaters of the Salt River and Little Colorado River. Two 24-ha experimental watersheds (WS 3 and WS 4) were re-instrumented to document post-wildfire peakflows. Previously-measured peakflows, associated with snowmelt runoff, never exceeded 0.0002 m^3/s. The first rainfall after the wildfire on the high-severity burned watershed WS 3, produced a flow of 0.252 m^3/s, 90 times the pre-fire flood peakflow. A subsequent storm that dropped over 65 mm of rain in 1 hour produced a peakflow (6.6 m^3/s, 2,350 times larger than pre-fire) that overtopped the gaging structure. Hillslope erosion on WS 3, the most severely burned of the two watersheds, was 109.2 Mg/ha the first year after the fire. Erosion on WS 4 with low-to-moderate severity fire was 61% of WS 3. Erosion rates declined significantly the second year. The Indian Fire of 2002 burned 553 ha in chaparral and ponderosa pine hills southwest of Prescott, Arizona. Sediment yields the first year was 64.8 Mg/ha, and it was 49.8 Mg/ha the second year. For these new wildfires, flood peakflows increased considerably and sediment yields were in the mid-range of Arizona wildfires. The recent large area, high severity wildfires have evidently pushed watershed responses out of their historical range of variability.

INTRODUCTION

Erosion and flooding are certainly the most visible and dramatic impact of wildfire apart from the consumption of vegetation. Fire management activities (wildfire suppression, prescribed fire, and post-fire watershed rehabilitation) can affect erosion processes in wildland ecosystems (Neary et al. 2005). Forest floor combustion, fireline construction, temporary roads, and permanent, unpaved roads receiving heavy vehicle traffic will increase storm runoff and associated erosion. Increased storm peakflows after wildfires will also increase erosion rates due to aggravated sheet, rill, and gully erosion, debris flows, and channel incision. Burned Area Emergency Rehabilitation work on watersheds will decrease potential post-fire erosion to varying degrees depending on the timing and intensity of rainfall (Robichaud et al. 2000).

Erosion: Post-wildfire erosion is a function of fire severity, which occurs primarily with moderate- to high-severity wildfires (DeBano et al. 2005). The most common types are sheet, rill, and gravity erosion. Dry ravel is another post-wildfire erosion type in which the gravity-induced, down slope, surface movement of soil grains, aggregates, and rock material delivers sediment to stream channels. It is a ubiquitous process in semiarid steep-land ecosystems that can be triggered by a number of processes. Dry ravel can equal or exceed rainfall-induced hillslope erosion after fire in chaparral ecosystems of the Southwest. Mass failures include slope creep, falls, topples, rotational and translational slides, lateral spreads, debris flows, and complex movements. Cannon (2001) describes several types of debris flow initiation mechanisms after wildfires in the southwestern United States. Of these, surface runoff, which increases sediment entrainment, was the dominant triggering mechanism.

Sediment yields after fires vary, depending on fire frequency, climate, vegetation, and geomorphic factors such as topography, geology, and soils. In some regions, over 60 percent of the total landscape sediment production is fire-related. Much of that sediment loss can occur the first year after a wildfire (DeBano et al. 2005). Increased side slope erosion after fires can alter channel equilibrium by transporting additional sediment into channels where it is stored until increased peakflows produced after fires erode the channel and move the stored material downstream. Channel geomorphology can be affected, and the deposition of sediments alters aquatic organism habitat.

Soil erosion following wildfires can vary from <0.1 Mg/ha/yr (<0.1 tons/ac/yr) in low-severity wildfire to over 369 Mg/ha/yr (164.6 tons/ac/yr) in high-severity wildfires on steep slopes (DeBano et al. 2005). DeBano et al. (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 high severity burned watersheds took 7 and 14 years, respectively. Nearly all fires increase sediment yield, but wildfires in steep terrain produce the greatest amounts. Sediment yields usually are the highest the first year after a fire and then decline in subsequent years. However, if precipitation is below normal, peak sediment delivery might be delayed until years two or three post-fire. In semi-arid areas like the Southwest, postfire sediment transport is very episodic in nature. There is growing evidence that short-duration, high intensity rainfall (>50 mm/hr in 10-to-15 minute bursts) over areas of about 1 km^2 (247 ac) produce flood flows that result in large amounts of sediment transport (Neary et al. 2005).

Peakflows: Peakflows are the maximum discharge during a flood event. They are important events in channel formation, sediment transport, and sediment redistribution in riverine systems. The effects of forest disturbance on storm peakflows are highly variable and complex. The magnitude of increased peakflow following fire is more variable than streamflow discharges, and is usually well out of the range of responses produced by forest harvesting. Increases in peakflow as a result of a high severity wildfire are generally related to the occurrence of intense and short duration rainfall events, slope steepness on burned watersheds, and the formation of soil water repellency during burning (DeBano et al. 1998, 2005; Neary et al. 2005). Fire has the potential to increase peakflows well beyond the normal range of variability observed in watersheds under fully vegetated conditions.

Neary et al. (2005) provided a good review of peakflow response to disturbance. These responses are influenced by fire severity. Intense, short duration storms have been associated with high stream peakflows and significant erosion events after fires. In the Intermountain West, high intensity, short duration rainfall is relatively common. Five minute rainfall rates of 213 and 235 mm/hr (8.38 and 9.25 in/hr) produced peakflows from newly burned areas that increased 5 times more than flow from adjacent, unburned areas (Croft and Marston 1950). Moody and Martin (2001) reported on a threshold for rainfall intensity (10 mm/hr or 0.39 in/hr in 30 minutes) above which flood peakflows increase rapidly in the Rocky Mountains. Robichaud (2002) collected rainfall intensity data on 12 areas burned by wildfire in the Bitterroot Valley of Montana. He measured precipitation intensities that ranged from 3 to 15 mm in 10 minutes. The high end of the range was equivalent to 75 mm/hr (greater than the 100-year return interval). It is these types of extreme rainfall events, in association with altered watershed condition, that produce large increases in stream peakflows.

Low severity, prescribed fires and wildfires have little or no effect on peakflows since they do not substantially alter watershed condition. Severe wildfires have much larger effects on peakflows. A 127-ha (314 ac) wildfire in Arizona increased summer peakflows by 5- to 150-fold, but had no effect on winter peakflows. Another wildfire in Arizona produced a peakflow 58 times greater than an unburned watershed during record autumn rainfalls (Neary et al. 2005). Campbell et al. (1977) documented the effects of fire severity on peakflows. A moderate severity wildfire increased peakflow 23-fold, but high severity wildfire increased peakflow response three orders of magnitude to 406.6-fold greater than undisturbed conditions. In New Mexico, Bolin and Ward (1987) reported a 100-fold increase in peakflow after wildfire in a ponderosa pine and pinyon-juniper forest. Watersheds in the Southwest are much more prone to these enormous peakflow responses due to interactions of fire regimes and site factors.

Another concern is the timing of stormflows or response time. Burned watersheds respond to rainfall faster, producing more flash floods. They also may increase the number of runoff events. After the Rattle Fire, Campbell et al. (1977) measured 6 events on an unburned watershed and 25 on a high-severity burned watershed. Hydrophobic soil conditions, bare soils, and litter and plant 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. Recovery times after fires can range from years to many decades. Still another aspect of the postfire peakflow issue is the fact that the largest discharges often occur in small areas. Biggio and Cannon (2001) examined runoff after wildfires in the western United States. They found that specific discharges (flow per unit area) were greatest from relatively small areas 1 km^2 or <0.4 mi^2. The smaller watersheds had peak specific discharges averaging 193.0 $m^3/sec/km^2$ (17,664.3 $ft^3/sec/mi^2$), while those in the next higher sized watershed category (10 km^2 or about 4 mi^2) averaged 22.7 $m^3/sec/km^2$ (2,077.6 $ft^3/sec/mi^2$).

Opportunities to study the impacts of watershed-scale fire on hydrologic processes in Arizona montane forests often present themselves following the occurrence of wildfire. Peak flows deserve special attention because of their impacts on erosion processes, and erosion is important because of downslope impacts on aquatic habitats (DeBano et al. 1998, Neary 2002). Post-fire erosion and peakflows following summer monsoonal rainfall events are documented in this paper. Case studies are presented from the Coon Creek Fire of 2000, the Indian Fire of 2002, and the historically large Rodeo-Chediski Fire of 2002.

METHODS

Coon Creek Fire 2000: The Coon Creek Fire originated on April 26, 2000, as an unattended campfire in the lower reaches of Coon Creek on the eastern side of the Sierra Ancha Mountains, Tonto National Forest. The wildfire eventually burned approximately 3,887 ha (9,600 ac) including parts of the Workman Creek Experimental Watersheds and the Sierra Ancha Wilderness area. The burned area originally supported a vegetative cover of mixed ponderosa pine and oak, ponderosa pine, and mixed conifer forests and chaparral shrubs. While most of the fire was low severity, approximately 20 percent of the area was burned at high severity. The fire crossed three watersheds (South Fork, Middle Fork, and North Fork) in the headwaters of Workman Creek (Gottfried and Neary 2003). These watersheds, which cover a total of 440 ha (1,087 ac), were established in 1939 and were the sites of several watershed experiments investigating the hydrology of mixed conifer forests and the impacts of forest management treatments on watershed resources. The undisturbed Middle Fork watershed burned at a high severity due to its high fuel load. Vegetation and the soil surface on two-thirds of the watershed were subject to high soil heating where litter, duff, and logs were completely consumed. Burn severities on the other two watersheds were low to moderate. The weirs and a flume at Workman Creek were reopened in June, 2000, to assess the impacts of the Coon Creek Fire on streamflow volumes, peak flows, and soil erosion and sedimentation rates. The Main Dam, a compound 90° V-notch weir and Cipolletti weir, measures streamflows from the entire three-watershed area. The South Fork and North Fork watersheds are gauged by 90° V-notch weirs and streamflows from the main part of Middle Fork are measured at a trapezoidal flume. Sediment export was measured at the Main Dam Workman Creek weir and by means of channel cross-sections.

Indian Fire 2002: This fire occurred from May 15-20, 2002. It started southwest of Prescott, AZ, near Indian Creek Road in the Prescott National Forest and burned into the city limits. The fire consumed 553 ha (1,365 ac) of ponderosa pine and chaparral vegetation. Some areas of high severity fire were instrumented with sediment fences to determine soil loss from 0.4 ha (1 ac) burned but untreated and other burned and rehabilitated areas (Robichaud and Brown 2002). No stream gauges were located within the fire perimeter, so flood peakflows were not assessed.

Rodeo-Chediski Fire 2002: This historic wildfire was actually two fires that ignited on the White Mountain Fort Apache Reservation and then merged into one devastating burn. Burning to the northeast, the merged Rodeo-Chediski fire then moved onto the Apache-Sitgreaves National Forest, along the Mogollon Rim in central Arizona, and into many of the White Mountain communities scattered along the Mogollon Rim from Heber to Show Low. The fire burned 187,300 ha (462,606 ac) in total by July 13th. Two nearly homogeneous watersheds, 24 ha (60 ac) each, had been established along Stermer Ridge at the headwaters of the Little Colorado River in 1972-73. The watersheds were gauged with 91 cm (3-foot H-flumes) that remained in place. Following cessation of the Rodeo-Chediski Fire, the flumes were refurbished and re-instrumented with water-level recorders and a weather station to study the impacts of varying fire severities on hydrologic processes. One of the Stermer Ridge watersheds experienced a high severity stand-replacing fire, while the other watershed was exposed to a low-to-medium severity stand-modifying burn. Sediment loss was measured by erosion pins since the H-flumes did not contain any structures or devices for measuring sediment loss. Sixty-five percent of the 635 mm (25 in) of annual precipitation falls from October to April, much of it as snow, and the remainder in rainstorms from July to early September. Summer storms, while often intense, rarely produced significant peakflows before the watersheds were burned.

RESULTS AND DISCUSSION

Coon Creek Fire 2000

Peakflows: Several record peak flows have been estimated at the Workman Creek Main Dam weir site since the wildfire. Middle Fork was gauged by a flume that did not have any sediment-determining structure. Most of the peakflows and sediment yield measured at the main weir originated in the Middle Fork watershed. A 15-minute rainfall burst at an intensity of 66 mm/hr (2.6 in/hr) on Middle Fork in June 2000 produced a peak flow that was more than 7-times (57.3 m^3/sec or 2,023 ft^3/sec) that of the previous highest peak flow of 8.18 m^3/sec (289 ft^3/sec) measured on October 10, 1972 (Neary and Gottfried 2002). The streamflow overtopped the Main dam weir, and, therefore, peak flow was estimated from high water marks. Two other peak flow events were observed in August, 2001. The higher of these peak flows, between 11.6 and 11.9 m^3/sec (409 and 420 ft^3/sec), was recorded on August 11, 2001, when a thunderstorm produced a rainfall event of approximately 33 mm/hr (1.3 in/hr) in intensity.

Sediment Loss: Severe surface soil erosion and sub-channel scouring were observed on Middle Fork following the June 2000 storm but no measurements were made because the control sections had not been instrumented at the time. Currently, erosion and sedimentation information are being measured on a series of channel cross sections that have been established on Middle Fork and on South Fork above the weirs. Sediment also is being measured at the settling basins behind the weirs at Main Dam, South Fork, and North Fork. Measurements are made on series of cross-sections that extend at 1-m (3 ft) intervals parallel to the cutoff walls. Most of these data have not been fully analyzed. However, the August, 2001, storms produced more than 41.3 m^3 (1,456 ft^3) of sediment in the Main Dam basin, which had been cleaned less than two month earlier, compared to 14.9 m^3 (526 ft^3) measured between late June and December of 2000 (Gottfried and Neary 2003). Most of the sediment appeared to originate from Middle Fork although some should be attributed to a main forest system road that runs parallel to the channel below the confluence of the three forks and crosses Middle Fork at one point. For the first 20 months after the fire the yield was 56.2 m^3 (1,982 ft^3), most likely a gross underestimate due to the large weir-overtopping flows. A sediment yield of 148.9 Mg in 20 months from the 440 ha (1,087 ac) of burned area would be considered an average amount even if it all came from the 166.4 ha (411 ac) Middle Fork watershed (Gottfried and Neary 2003). A pebble count of sediment behind the Main Dam in June 2001 indicated that 48% of the sediments were sand and 36% were cobbles. Approximately 3% of the sediments were in the boulder category >256 mm in diameter.

Indian Fire 2002

Peakflows: Flood peakflows were not assessed at this site. However, substantial overland flows were observed by the senior author during the first rainfall event after the fire, and the evidence of high runoff was observed during the forst 3 monsoon seasons after the fire. Due to the limited area of high-severity fire, significant flood flows were not generated off of the area within the fire perimeter.

Sediment Loss: After the first monsoon rain period, sediment yield from plots on the Indian Fire burned at high severity was about 50 Mg/ha (22 tons/ac). Most of this sediment was delivered by one storm event that contained an intense rainfall burst. The maximum rainfall intensity was 117 mm/hr (4.62 in/hr). Addition of wood chips or straw mulch onto the high-severity burned soil reduced erosion by 80%. This rehabilitation technique mimicked the normal forest floor covering and returned most hydrologic function to the site. Total sediment yield from the burned but un-rehabilitated area was 64.8 Mg/ha at the end of 2002, and 49.8 Mg/ha the second year (2003). By 2005, sediment yield had become negligible in treated and untreated burned areas alike due to vegetation regrowth.

Rodeo-Chediski Fire 2002

Peakflows: Following the Rodeo-Chediski Fire of 2002, peakflows were orders of magnitude larger than earlier recorded. The estimated initial peakflow on the WS 3 watershed that experienced high severity stand-replacing fire was almost 0.25 m^3/sec (8.9 ft^3/sec) or nearly 900 times that measured pre-fire (Ffolliott and Neary 2003). The peakflow on the watershed subjected to low-to-medium severity fire was estimated to be <50%, but still far in excess any previously observed ones. A subsequent and higher peakflow on the severely burned watershed was estimated to be 6.57 m^3/sec (232 ft^3/sec) or about 2,232 times that measured in snow-melt runoff prior to the wildfire. This latter peakflow increase represents the highest known relative post-fire peak flow increase that has been measured in the ponderosa pine forest ecosystems of Arizona or, more generally, the southwestern United States. However, the specific discharge of 1.02 m^3/sec/km^2 (94.2 ft^3/sec/mi^2) was on the lower end of range of discharges measured by Biggio and Cannon (2001).

Sediment Loss: The measurements of soil pedestals suggest that 56 to 67 Mg/ha (25 to 30 tons/ac) of soil were eroded from the severely burned watershed in response to the first summer monsoon rains (Garcia et al. 2005). Between 34 to 45 Mg/ha (15 to 20 tons/ac) of soil were lost from the lightly-to-moderately burned watershed (Figure 1). Soil erosion rates on the severely burned and lightly-to moderately burned watersheds after the first winter precipitation and snowmelt-runoff period following the wildfire were 49 to 27 Mg/ha (22 and 12 tons/ac), respectively. Erosion rates following the second summer monsoon rains were statistically similar between watersheds, averaging about 25 Mg/ha (11 tons/ac) for both watersheds. During the second winter, erosion rates increased again to the 40 to 50 Mg/ha range but there was no statistical difference between the burn severities.

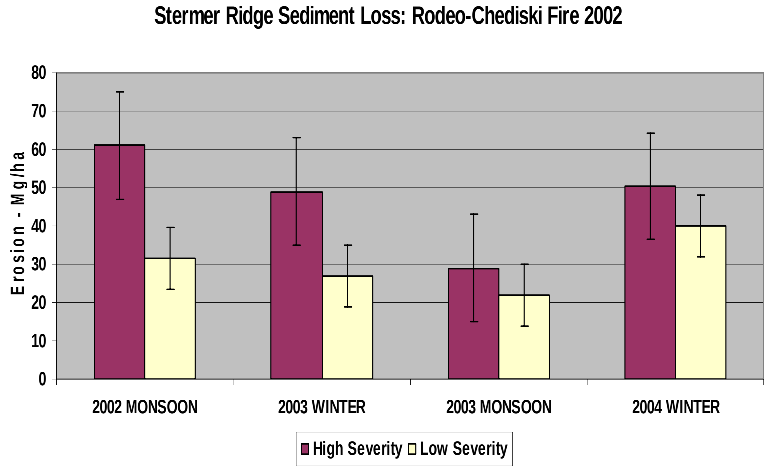

Figure 1 Sediment loss from Stermer Ridge Watersheds, Rodeo-Chediski Wildfire 2002, first four precipitation periods (Adapted from Garcia et al. 2005 and Stropki et al. In Press).

SUMMARY AND CONCLUSIONS

Following wildfires, flood peak flows can increase dramatically, severely affecting stream physical conditions, aquatic habitat, aquatic biota, and sediment yield. The potential exists for peak flood flows to jump to 2,300 times that of pre-wildfire levels as observed after the Rodeo-Chediski Fire. Sediment yields in these study areas were at about the middle of the range observed in other wildfires in the Southwest (Neary et al. 2005). Land managers must be aware of these potential watershed responses in order to adequately and safely manage their lands and water resources in the post-wildfire environment. The recent large-area, high-severity wildfires have evidently pushed watershed peakflow responses out of their historical range of variability, and have the potential to do the same to sediment yield.

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