Impacts of Wildfires on Hydrologic Processes in Forest Ecosystems: Two Case Studies

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Abstract

The Coon Creek Wildfire in 2000 and the Rodeo-Chediski Wildfire in 2002 devastated large areas of forest in north-central Arizona. The presence of historic hydrologic control structures on the three Workman Creek Watersheds within the Coon Creek burn area and the two Stermer Ridge Watersheds within the Rodeo-Chediski area provide opportunities to study the impacts of watershed-scale fire on hydrologic processes in the forest ecosystems of the Southwest. Fire intensities and severities varied among the watersheds within each area. Streamflow regimes, erosion-sedimentation processes and other on-site hydrologic characteristics are being monitored. High intensity summer thunderstorms following the fire at Workman Creek produced three peak flows that exceeded the historic peak flow. One storm in June 2000 produced a peak of approximately 2,000 cubic feet per second, 7 times the previous record peak flow. The severely burned watershed at Stermer Ridge produced a peak flow of 232 cubic feet per second, an increase of 2,350 times the historic high flow, after an intense summer storm. Hydrophobic soils were identified within the severely burned areas. Preliminary measurements at the Main Dam sediment basin at Workman Creek and at erosion pin sites at Stermer Ridge indicate increases in erosion and sedimentation from the severely burned watersheds. Continued monitoring of the watersheds will provide additional information about the impacts of wildfires on hydrologic processes in southwestern forest ecosystems.

Keywords: hydrologic processes, erosion and sedimentation, wildfires, forested ecosystems, watershed studies, Arizona

Introduction

Two historical wildfires in north-central Arizona in 2000 and 2002 provided opportunities to study the impacts of watershed-scale fire on hydrologic processes in the forest ecosystems of the Southwest. Streamflow regimes, erosion-sedimentation processes, precipitation, and other on-site hydrologic characteristics are being monitored and evaluated on the Workman Creek and the Stermer Ridge Watersheds following recent large and devastating wildfires. The Coon Creek Fire of 2000 burned 9,644 acres on the Tonto National Forest, including the three experimental watersheds at Workman Creek on the Sierra Ancha Experimental Forest, while the Rodeo-Chediski Fire in 2002 burned approximately 475,000 acres on the White Mountain Apache Reservation and Apache-Sitgreaves National Forests. The Stermer Ridge Watersheds are located within the burned area on the Apache-Sitgreaves National Forests, south of the towns of Heber and Overgaard. The hydrologic control structures at both locations had been mothballed after previous watershed research studies were completed, but had been left in place. The control-sections were re-instrumented and weather stations re-established immediately

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following the respective wildfire to provide a basis to study the relative impacts of light, moderate, and severe fire severities on selected hydrologic processes. Preliminary findings with respect to peak flows, annual streamflow regimes, on-site changes in soil properties, and sediment transport are reported; however, much of the data still need to be analyzed. Vegetation also is being monitored but these data are not reported here. Information of this kind is needed by land managers to plan and manage for on-site post-fire watershed rehabilitation and to understand the impacts of fire on downstream riparian corridors and anthropological infrastructures.

Coon Creek Fire

The Coon Creek Fire originated on April 26, 2000 at an unattended campfire in the lower reaches of Coon Creek on the eastern side of the Sierra Ancha Mountains. The fire eventually burned approximately 9,644 acres including parts of the Workman Creek Watersheds, within the Sierra Ancha Experimental Forest, and the Sierra Ancha Wilderness. The burned area originally supported a vegetative cover of mixed ponderosa pine (*Pinus ponderosa* var. *scopulorum*) and Gambel oak (*Quercus gambelii*), ponderosa pine, and mixed conifer forests. The fire crossed the three experimental watersheds (South Fork, Middle Fork, and North Fork) at the headwaters of Workman Creek (Gottfried and Neary 2001, Gottfried et al. 2002). These watersheds, which cover a total of 1,087 acres, were established in 1939 to investigate the hydrology of mixed conifer forests and the impacts of forest management treatments on watershed hydrology. The area is between 6,590 and 7,724 feet in elevation and received an average of about 36.2 inches of annual precipitation between 1960 and 1991 (Martinez 1993). Two-thirds of the annual precipitation occurs during the October through May period, mostly as snow, and produces most of the annual streamflow.

The control sections on the three watersheds were "mothballed" in 1983 following more than 40 years of continuous hydrologic monitoring and evaluations. The Middle Fork of Workman Creek, which had been the hydrologic control for the earlier experiments, supported an undisturbed old-growth mixed conifer forest of ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), and white fir (*Abies concolor*) prior to the fire. The Middle Fork stand averaged more than 200 square feet of basal area per acre and fuel loadings averaged from 40 to 50 tons per acre (USDA Forest Service 2000) but might have been heavier in some areas. The forests on South Fork and North Fork had been modified by the earlier experimental treatments and contained mosaics of grass, shrub, and forest covers at the time of the fire (Gottfried and Neary 2001, Gottfried et al. 2002). While most of the burn severities were low, approximately 20 percent of the area, including Middle Fork, was burned at high severities. The vegetation and soil surface on two-thirds of this watershed were subjected to high soil heating where litter, duff, and logs were completely consumed exposing the surface soil, which was reddish in color. Burn severities on the other two watersheds were generally low-to-moderate.

Streamflow measurements

The Rocky Mountain Research Station and Tonto National Forest opened the weirs and a flume at Workman Creek in June 2000 to assess the impacts of the Coon Creek Fire on streamflow volumes, peak flows, and soil erosion and sedimentation rates. Main Dam, a combination 90° V-notch weir and 7-foot Cipolletti weir, measures stream flows from the entire three-watershed area. The South Fork and North Fork watersheds are gauged by 90° V-notch weirs, and streamflows from the 411-acre main part of Middle Fork are measured at a trapezoidal flume. A weather station was re-established at Peterson Meadow within Middle Fork. A Natural Resources Conservation Service snow course and/or SNOTEL station has been maintained continuously on Middle Fork since 1951. Statistically significant relationships have been developed for the pre-fire period between peak snow water equivalent data and winter snowmelt runoff and mean daily peak flows for all hydrologic control sections and should be useful in analyzing the impacts of the wildfire on snowmelt runoff parameters (Gottfried et al. 2002).

Peak flows

Several record peak flows have been estimated at the Main Dam site since the wildfire. A 15-minute rainfall at an intensity of 2.6 inches per hour on Middle Fork in June 2000 produced a peak flow that was more than 7 times that of the historic high peak of 289 cubic feet per second that was measured on October 7, 1972 (Neary and Gottfried 2002). The earlier peak flow was related to approximately 11.67 inches of precipitation that was recorded in Middle Fork from October 3 through October 7, 1972. The

June 2000 streamflow overtopped the weir and, therefore, was estimated from high water marks.

Two other peak flow events were also observed in August 2001. The higher peak flow, of about 420 cubic feet per second, was recorded on August 11, 2001, when a thunderstorm produced a rainfall event of approximately 1.3 inches per hour in intensity. The partially cleaned settling basin and associated hydrologic structures at Main Dam were filled with sediment after this event. Observations at South Fork and North Fork showed slight increases in trapped sediments behind the weir walls, indicating that most of the streamflow and sediments originated from the severely burned Middle Fork. The Main Dam was overtopped by both events and the instrument shelters were partially submerged in the second event. These two flows contained large amounts of sediment and several logs, making accurate streamflow calculations difficult.

On-site changes in soil properties

The Burned Area Emergency Rehabilitation (BAER) assessment indicated that 330 acres or 29% of the burned area in Workman Creek would have a high to very high response to precipitation events because of moderate to strong water repellency and minimal vegetative ground cover (USDA Forest Service 2000). The report estimated a 50% reduction in infiltration and that the soil erosion hazards on sites like Middle Fork are high.

Sediment transport

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-meter intervals parallel to the cutoff walls. Most of these data have not been fully analyzed; however, the August 2001 storms produced more than 1,456 cubic feet of sediment in the Main Dam basin, which had been cleaned less than two month earlier, compared to 526 cubic feet measured between late June 2000 and December 2000 when no unusual streamflow events occurred. Most of the sediment originated 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. A pebble count of sediment behind the Main Dam in June 2001 indicated that 48% of the sediments were sand (< 0.08 inch in diameter) and 36% were cobbles (2.5-10.1 inches). Approximately 3% of the sediments were in the boulder category (>10.1 inches).

Rodeo-Chediski Fire

This historic fire actually consisted of two fires that ignited on the Fort Apache Reservation and then merged into one devastating fire. The cause of the Rodeo Fire, which began a few miles from Cibecue on the Reservation on June 18, 2002, was arson. A seemingly lost person set the Chediski Fire as a signal fire a few days later. This second fire spread out of control and eventually merged with the on going and still out of control Rodeo fire. Burning northeastwardly, the re-named 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 between Heber and Show Low. Over 30,000 local people were forced to flee the inferno. The fire had burned 276,507 acres of Apache land and 462,606 acres in total by the time that most of the firefighters had left the area on or about July 13. Nearly 500 buildings had been destroyed, with over one-half of the burned structured being the houses of local residents or second-homes of summer visitors.

Streamflow measurements

Two nearly homogeneous, 60-acre watersheds had been established along Stermer Ridge at the headwaters of the Little Colorado River in 1972-73 as a cooperative project of the Rocky Mountain Research Station, USDA Forest Service, and the University of Arizona to obtain baseline hydrologic and ecological information on watersheds located in ponderosa pine forests on sedimentary soils (Ffolliott and Baker 1977). Cretaceous undivided material with mineralogy similar to that of the Coconino sandstone formation lies beneath the watersheds. The soils have been classified as Typic Eutroboralfs with sandy loam textures (Laing et al. 1987). The two watersheds were situated on relatively flat topography, with few slopes exceeding 10 percent. Their elevations range from 6,800 to 7,000 feet. The most recent timber harvest removed approximately 45 percent of the merchantable sawtimber by group selection in the early 1960s. Sixty-five percent of the 20-to-25 inches 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 stormflows before the watersheds were burned.

The two watersheds had been "moth-balled" in 1977-78 after completion of the baseline watershed measurements. However, the control sections (3-foot H-flumes) were left in place. Following cessation of the Rodeo-Chediski Fire, these control sections were re-furbished and re-instrumented with water-level recorders and a weather station was re-established on the site to study the impacts of varying fire severities on hydrologic processes. A fire severity classification system that relates fire severity to the soil-resource response to burning (Hungerford 1996) was used to determine the relative portions of the watersheds that were burned at low, moderate, and high severity (Wells et al. 1979). This extrapolation indicated that one of the Stermer Ridge watersheds experienced a high severity stand-replacing fire, while the other watershed had been exposed a low-to-medium severity stand-modifying fire.

Post-fire peak flows

Summer storm flows on the Stermer Ridge watersheds had been uncommon. The highest peak flow measured in a summer storm flow event in the 1972-76 pre-fire period was about 0.10 cubic feet per second. However, high-water marks observed at the control sections in the first visit of researchers to the watersheds following the fire indicated peak flows in orders of magnitude larger than earlier recorded (Ffolliott and Neary 2003). The estimated peak flow on the watershed that experienced the high severity stand-replacing fire was almost 8.9 cubic feet per second or nearly 90 times that measured in 1972-1976 period. Peak flow on the watershed subjected to the low-to-medium stand-modifying fire was about one-half less in magnitude but still far in excess of the previous observations. A subsequent rainfall event of unknown intensity generated even higher peak flows. Precipitation records are not available for Stermer Ridge for these early storm periods. On the severely burned watershed, the peak flow following this second event was estimated to be 232 cubic feet per second or about 2,350 times that measured earlier. This flow represents the highest known post-fire peak flow measured in the ponderosa pine forest ecosystems of Arizona or, more generally, elsewhere in the southwestern United States.

On-site changes in soil properties

The initial effect of the Rodeo-Chediski Fire on soil properties has been manifested largely through changes in infiltration rates and transpiration. The reduction in infiltration because of the widespread formation of water-repellent soil following the fire decreased the amount of water entering the soil as a result of the monsoon storm events in the two-months following the fire. However, at the same time, the extensive loss of vegetation to burning meant that less water was removed from the soil body by the transpiration process. The net effect of these "compensating changes" is expressed by the spatial and temporal measurements of soil moisture storage that began shortly after the fire was controlled.

The fire as a result of the extensive loss of protective vegetative cover exposing mineral soil intensified erosion forces on the watersheds. Soil erodibility also increased because of the volatilization of soil organic material and a destruction of aggregated soil structures. The reduction in infiltration rates on water-repellent soils and consequent increase in overland flows increased the dislodgement and transport of soil particles as witnessed by the large accumulations of sediment in the stream channels.

Sediment transport

Sediment transport immediately following the fire can only be approximated because erosion pins had not been established. The BAER assessment estimated that the average post-fire sediment delivery for the total burned area would be 68 cubic feet per acre per year or an increase of more than 3,200 percent over pre-fire conditions (USDA Forest Service 2002). Based on observations of post-fire soil pedestals and measurements of sediment accumulations in the stream channel, it is estimated that a sediment load in excess of 30-to-35 tons per acre passed through the control section on the watershed that experienced the high intensity stand-replacing burn in response to the summer monsoonal storms. It is likely that sediments in excess of 15-to-20 tons per acre were generated on the watershed subjected to the low-to-medium stand modifying fire. These values exceed the previous estimates for maximum rate of soil erosion for the watershed areas of 3 to 5 tons per acre per year (Laing et al. 1987).

Erosion pins were installed on the watersheds in October to estimate the changing magnitudes of subsequent soil erosion rates and sediment loads in terms of the respective fire intensities observed. Measurements made in April 2003 indicated that the intervening erosion was about 23 tons per acre on the watershed that burned at a high severity and nearly 12 tons per acre on the watershed that burned at the low-to-medium severity. The relative amounts of this eroded soil that moved into the stream channels is unknown at this time.

Hydrologic impacts of historical Arizona forest fires

Other wildfires impacting peak flows have been measured in the forests of Arizona (Neary et al. 2003). Rich (1962) reported on the impacts of a 60-acre wildfire within the upper section of the South Fork of Workman Creek in July 1957. He measured a peak of 78 cubic feet per second after a high intensity summer storm that had produced between 3.50 and 4.05 inches of precipitation with intensities exceeding 2.00 inches per hour. The storm removed more than 41,800 cubic feet of soil from the 60-acre site, most of which was re-deposited on flat areas below the burned area or in the stream channel. The Rattle Burn in May 1972 covered two of three watersheds in ponderosa pine forests southwest of Flagstaff (Campbell et al. 1977). One watershed was severely burned, one was moderately burned, and one was not burned. Average annual runoff for the first three years after the fire was 1.1 inches for the severely burned watershed, 0.8 inch for the moderate area and 0.2 inch for the unburned area. Peaks averaged 10.98 cubic feet per second for the severely burned area for two large post-fire precipitation events while the moderate and unburned areas had similar responses, averaging 0.34 and 0.22 cubic feet per second.

Some post-fire impacts have been difficult to analyze on a watershed-basis because of instrumentation or design limitations. One example is the Dude Fire of 1990, one of the more devastating wildfire in Arizona's history, which burned 27,120 acres of mostly ponderosa pine forests surrounding Dude, Bonita, and Ellison Creeks in central Arizona, destroyed over 60 homes and structures, and, sadly, resulted in the loss of six lives. Because streamflow measurements are not available for the individual watersheds impacted by the Dude Fire, it is not possible to directly assess the fire's impacts on the peak flows from these burned watersheds. However, streamflow records from the U.S. Geological Survey gauging station situated on Tonto Creek above Roosevelt Lake, which monitors a 675 square mile watershed including the Dude Fire, can be used to "qualitatively consider" the Dude Fire in the general context of its effects within a broader and larger river-basin scale (Neary et al. In press). Streamflow measurements at this gauging station for the year of the fire (1990) were compared to mean daily streamflow records for two years preceding (1988-89) and two years following (1991-92) the fire. The results indicated significantly higher peak flows in the initial post-fire period than in the other periods following summer monsoon rainfall events of similar magnitudes and time periods. The initial storm flow following the fire had a peak that was 80 times the base flow at the time. While the proportion of this increase that is attributable to the fire is unknown, there can be little doubt that the fire played a significant hydrologic role in generating this increase.

Summary

The post-fire impacts on hydrologic processes reported in this paper have been documented more-or-less on a controlled watershed-basis; that is, either pre- or post-fire measurements were made on a watershed or an unburned control watershed that were available for comparison purposes. While specific case studies are presented, the increases in peak flows, streamflow regimes, and erosion-sedimentation rates that have been observed are likely to bracket the post-fire peak flows that might be expected in Arizona montane forests. It is further assumed that the post-fire peak flows observed immediately following the Rodeo-Chediski Fire represent the "upper-end" of the range of these values. The results and observations reported here are preliminary; research is continuing on the Workman Creek and Stermer Ridge watersheds and more comprehensive information will be available in the next few years.

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