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POST-WILDFIRE WATERSHED FLOOD RESPONSES

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1. INTRODUCTION

Fire exerts a tremendous influence over forest ecosystems in the Southwest depending on it's intensity, duration, and frequency (DeBano et al. 1998). It is an important natural disturbance that has played a significant role in the development of forest, shrub, and grassland ecosystems. The "natural" fire that shaped these ecosystems occurred across a continuum that ranged from light burns to catastrophic, stand-replacing conflagrations. Thus, fire disturbance to these ecological systems produces a continuum of effects on watershed resources.

Land managers and other interested people should understand the past role of natural fires in shaping southwestern ecosystems, and how altered fire regimes affect current management. The impacts on watershed resources are particularly important since they directly influence other natural resource values and public safety.

During most of the 20th century, foresters focused attention on the multiple resource damages produced by wildfire (Pyne et al. 1996). Indeed, catastrophic fires produced or enhanced by natural events (drought, insect outbreaks, lightning, etc.) did result in serious impairment to watershed resources. In the past decade, forest managers have gained a great understanding of fire's significance in forest ecosystems by observing both the catastrophic effects of decades of an "unnatural" disturbance (fire exclusion), as well as the beneficial effects of well-managed prescribed fire programs.

As a physical-chemical process, fire is a continuum that results from interactions of intensity, climate, slope, topography, soils, and area (DeBano et al. 1998). Thus the impact on water resources also occurs on a continuum (Neary 1995). Our ability to describe those impacts is a function of the scientific information obtained on a limited range of fires. Fires and watershed resource impacts will continue to occur on new and unique combinations across this continuum.

Fire intensity refers to the rate at which a fire is producing thermal energy (DeBano et al. 1998). The higher the intensity, the more severe the impacts on water resources. Intensity is a function of climate, temperature, rate of spread, heat yield, and fuels. Temperatures may range from 50 to 1,500^{o} C. Rates of spread vary from 1 m in 2 weeks (peat fire) to 6-7 km/hr (large wildfire). Heat yields range from 2.1 to 2,100 kJ/kg, and fuel loads increase from grasses (1 Mg/ha) to heavy timber (160 Mg/ha). Climate, slope, topography, soils, and watershed size are other continuums that act to affect fire intensity. The combination of fire intensity and duration produce resource impacts that we then classify as fire severity (low, moderate, and high).

Watersheds are used as the basic unit of measurement for ecosystem analysis since water is the main transport mechanism that integrates ecosystem processes (Brooks et al. 2002). Watersheds function on all temporal and spatial scales. They are also a focus for important human activities (water supply, recreation, resource production, etc.) that disturb watershed processes and result in ecosystem changes (Neary and Hornbeck 1994). An important part of understanding the impacts of fire on water resources is to comprehend the processes involved. Much information has been incorporated here to describe the range of these impacts. Since fire is a continuum and data are scarce for some portions of this continuum, not all situations will be adequately described.

Watershed condition, or the ability of a watershed system to receive and process precipitation without ecosystem degradation, is an accurate predictor of the potential impacts of fire on water resources. The surface cover of a watershed

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consists of organic forest floor (thin to thick), vegetation (variable cover), bare soil, and rock. Fire may destroy the organic forest floor and vegetation, and alter the infiltration and percolation capacity of bare soil. In some soil-vegetation complexes, water repellency develops and greatly reduces water infiltration (DeBano 1971). This alters watershed (hydrologic) condition, with erosion increasing as watershed condition goes from good to poor.

Therefore, an understanding of processes is a key factor in successful interpretation of the effects of prescribed fires and wildfires on water resources (Neary 1995). Fire is one of the most frequent and profound watershed disturbance agents in the Southwest (Swanson 1981). The purpose of this paper is to briefly summarize what is known about the effects of fire on watershed resources in the Southwest. The resources of primary concern are vegetation, soils, streamflow quantity, water quality, and wildlife.

2. STREAMFLOW AND FLOODS

2.1 Streamflow

Fires affect the quantity of water in a forest ecosystem by affecting key water cycle processes. Fires may reduce interception, thereby reducing moisture storage, increasing water yields, and creating greater runoff with smaller storms. Burning of forest floor reduces litter storage of precipitation (0.5 mm/cm of litter lost) and increases overland flow. Fires temporarily eliminate transpiration, increasing soil moisture and streamflow. The burning of surface organic matter reduces infiltration, thereby increasing overland flow and surface stormflow. Fires usually increase streamflow in most forest ecosystems, but can decrease streamflow in snow-dominated and fog-drip systems. In the short-term, fires alter baseflow and increase stormflow volume and response. On burned watershed areas, response to storm events is greater with shortened time to peak flow, increased susceptability to flash floods, and higher peak flows. Fires increase snow accumulation in burns <4 ha due to a snow trapping effect, but reduce snowpacks where burns exceed 4 ha as a result of higher evaporation and sublimation.

2.2 Water Yield

The effects of disturbances, primarily harvesting, on water yield from forested watershed studies throughout the world have been well documented and reviewed (Anderson et al. 1976, Bosch and Hewlett, 1982, Neary and Hornbeck 1994). For the most part, water yields increase when mature forests are harvested, burned, blown down, or attacked by insects. The only exceptions occur where fog is abundant or snowfall accounts for a majority of the annual precipitation. The amount of measured water yield increases the first year after fire disturbance vary greatly at one location or between locations depending on fire intensity, climate, precipitation, geology, soils, watershed aspect, tree species, proportion of the forest vegetation burned. Since measured increases in water yield are primarily due to elimination of plant cover, with subsequent reductions in the transpiration component of ET, yield increases have been found to be greater in ecosystems with high ET. Streamflow increases produced by forest disturbance decline as both woody and herbaceous vegetation re-grow. This recovery period may range from a few years to decades.

Most of the water yield responses available from the scientific literature deal with the effects of harvesting, where increases from harvesting range from 0 to 126% (Neary and Hornbeck 1994). Water yield increases from prescribed fires and wildfires in the Southwest are variable, but are generally less than 150% for prescribed fires and low-severity wildfires. Moderate-to-high severity wildfires can cause significant increases in water yield (Hibbert 1971, DeBano et al. 1996). The formation of water repellent layers is often associated with large increases in water yield (DeBano 1981, DeBano et al. 1998).

2.3 Baseflows

Baseflows are important in maintaining perennial flow through the year. Wildfires in 1996 and 2000 resulted in a number of anecdotal reports of springs beginning to flow after years of being dry. This sort of response is common in the Southwest and regions such as Central Texas when an area is cleared or burned (Thurow 2001, personal communication). Often trees such as juniper or live oak have increased in density and size along with the onset of effective fire control about a century ago. Over-grazing is also partly to blame for this situation. Excessive grazing reduced the herbaceous cover and fine fuels in many areas of the Southwest, preventing lightning-ignited ground fires from spreading. As trees begin to dominate ecosystems such as fire-climax grassland savannas, the trees alter the water balance because they have substantially greater interception loss and transpiration capacity. The local soils and geology determine whether water yield occurs as spring flow or groundwater recharge. The seasonal patterns of the amount and timing of precipitation and potential evapotranspiration determine whether there is any excess water to contribute to water yield (i.e., on arid sites all precipitation would be lost to ET and, thus, essentially nothing would percolate fast enough beyond the root system and/or evaporation from the soil surface to recharge springs or aquifers). Some shrub sites may yield substantial amounts of water, while others may yield nothing (Wu et al. 2001).

2.4 Peakflows

Flood peakflows are a special subset of streamflow regimes that deserve considerable attention. The effects of forest disturbances on storm peakflows are variable and complex because they are the result of different levels of disturbance. They produce some of the most profound impacts of concern for forest managers. Increased flood peakflows following fire are more variable than streamflow discharges, and are usually well beyond the normal range of responses produced by forest harvesting. Increases in peakflow as a result of a high severity wildfire are generally related to a variety of processes including the occurrence of intense and short duration rainfall events, slope steepness on burned watersheds, and the formation of soil water repellency after burning (DeBano et al. 1998, Brooks et al. 2002). Post-fire flood events with excessively high peakflows are often characteristic of flooding hydrologic regimes.

3. FLOODS

3.1 Hydrologic Significance

Peakflows are important events in channel formation, sediment transport, and sediment redistribution in riverine systems (Rosgen 1996, Brooks et al. 2002). These extreme events often lead to significant changes in the hydrologic functioning of the stream system and, at times, a devastating loss of cultural resources. Floods are important considerations when designing structures (e.g. bridges, roads, dams, levees, culverts, commercial and residential buildings, downstream development structures, etc.). Fire has the potential to increase flood peakflows well beyond the normal range of variability observed among watersheds having fully vegetated conditions. For this reason, understanding of peakflow response to fire is one of the most important aspects of understanding the effects of fire on water resources.

3.2 Peakflow Mechanisms

There are a number of mechanisms that occur singly or in combination to produce increased post-fire peakflows (Neary 2002). These include mechanisms such as unusual rainfall intensities, rapid melt of snowpack, destruction of vegetation, reductions in litter accumulations and other decomposed organic matter, antecedant soil moisture conditions, alteration of soil physical properties, and development of soil water repellency.

A special circumstance sometimes occurs during post-wildfire peakflows that contributes to the large responses (up to three orders of magnitude increase). Cascading debris dam failures have the potential to produce much higher peakflow levels than would be expected from given rainfall events on bare or water repellent soils. This process consists of the establishment of a series of debris dams from large woody debris in and adjacent to stream channels, build up of water behind the dams, and sequential failure of the first and subsequent downstream debris dams. Concern about this process has led to the use of debris removal as one type of Burned Area Emergency Rehabilitation (BAER) channel treatment, debris removal. Channels particularly prone to this process would include those with large amounts of woody debris, and a high density of riparian trees or boulders which could act as the dam formation mechanism. After the 1991 Dude Fire in Arizona, Rinne (1996) reported that few of the tagged pre-fire woody debris moved after a significant post-fire flood event. On the other hand, some unusually high flood flows after the 2000 Cerro Grande Fire in New Mexico left distinct evidence of woody debris dam formation and failure (Kumunyian 2001, personal communication).

3.3 Fire Effects

Anderson et al. (1976) provided a comprehensive review of peakflow response to disturbance. These responses are strongly influenced by fire severity. Low severity prescribed burning has little or no effect on peakflow, since it does not generally alter watershed condition.

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 (Neary et al. 1999). In the Intermountain West, high intensity, short duration rainfall is relatively common (Farmer and Fletcher 1972). Five-minute rainfall rates of 213 and 235 mm/hr have been associated with peakflows from recently burned areas that were 5 times greater than adjacent, unburned areas (Croft and Marston 1950). A 15-minute rainfall burst at a rate of 67 mm/hr after the 2000 Coon Creek Fire in Arizona produced a peakflow that was more than seven times greater than the previous peakflow during 40 years of streamflow gauging. Moody and Martin (2001) reported on a threshold for rainfall intensity of 10 mm/hr (30 minute duration) above which flood peakflows increase rapidly in the Rocky Mountains. It is these types of extreme rainfall events, in association with altered watershed condition, that produce large increases in stream peakflows.

Peakflows after forest cutting may increase or decrease depending on location, the percentage of the watershed cut, precipitation regime, and season. Most studies show increases in peakflows of 9 to 100%. The concern with increases in annual flood peakflows is that the increases could lead to channel instability and degradation, and increased property damage in flood-prone urban areas.

Fire has a wide range of effects on stream flood peakflows. Low severity prescribed fires have little or no effect since they do not alter watershed condition. Severe wildfire has much larger effects on peakflows. A 127 ha wildfire in Arizona increased summer flood peakflows by 5- to 150-fold, but had no effect on winter peakflows (Rich 1962). Another wildfire in Arizona produced a peakflow 58-fold greater than any that ever occurred from an unburned watershed during record autumn rainfalls. Campbell et al. (1977) documented the effects of fire severity on peakflows. A moderate severity wildfire increased flood peakflow by 23-fold, but high severity wildfire increased peakflow response to 400-fold greater than from undisturbed conditions. Krammes and Rice (1963) measured a 870-fold increase in flood peakflow in California chaparral. 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, soils, geology, slope, and climate. Swanson (1981) estimated that over 70% of the long-term sediment production in the Southwest is due to fire. Fire-related sediment yields in steeplands in the Cascade Mountains are on the order of 30%, while those in the Appalachians are around 5%.

3.4 Flood Timing

One 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. Campbell et al. (1977) measured six events on an unburned watershed after the Rattle Burn and 25 events on a high-severity burned watershed. Hydrophobic 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. Another aspect of this phenomenon is the fact that recovery times may range from years to many decades.

4.0 RECENT RESULTS

4.1 Coon Creek Fire

The Coon Creek Fire originated on April 26, 2000, at an unattended campfire site in the lower reaches of Coon Creek on the eastern side of the Sierra Ancha Mountains. The wildfire eventually burned approximately 3,886 ha including parts of the Workman Creek 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 intensities were low, approximately 20% of the area was burned at high intensities. The fire crossed the three experimental watersheds (South Fork, Middle Fork, and North Fork) at the headwaters of Workman Creek (Gottfried and Neary 2001). These watersheds, which cover a total of 440 ha, were established in 1939 to be the site of several watershed experiments investigating the hydrology of mixed conifer forests and the impacts of forest management treatments on watershed resources.

The three watersheds were “mothballed” in 1983 following more than 40 years of continuous hydrologic monitoring and evaluation. The Middle Fork of Workman Creek, which had been the hydrologic control for the earlier watershed experiments and is the focus of this paper, supported an undisturbed old-growth mixed conifer forest prior to the fire. Forest vegetation on South Fork and North Fork had been modified by the earlier experimental treatments and contained mosaics of forest, shrub, and grass covers at the time of the fire. The Middle Fork burned at a high intensity. Vegetation and the soil surface on two-thirds of the watershed was subject to high soil heating where litter, duff, and logs were completely consumed. Intensities on the other two watersheds were low to moderate.

Streamflow Measurements

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 combination 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.

Post-Fire 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 66 mm/hour on Middle Fork in June, 2000, produced a peak flow that was more than 7-times that of the previous highest peak flow of 8.19 m^3/sec measured on October 10, 1972 (Neary and Gottfried 2002). The streamflow overtopped the 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 11.57 and 11.89 m^3/sec, was recorded on August 11, 2001, when a thunderstorm produced a rainfall event of approximately 33 mm/hr 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 less sediments trapped behind the weir walls, suggesting that most of the streamflows 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 peak flows contained large amounts of sediment and several logs, making streamflow calculations difficult.

4.2 RODEO-CHEDISKI FIRE

This historic wildfire was actually two fires that ignited on the Fort Apache Reservation and then merged into one devastating burn. The cause of the Rodeo Fire, which began a few miles from Cibecue on the Reservation on June 18, 2002, was arson, while the Chediski Fire was set as a signal fire by a seemingly lost person 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 from Heber to Show Low. Over 35,000 people were forced to flee the inferno. The fire had burned 111,901 ha of Apache land and 187,212 ha 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 watersheds, 24.3 ha each, 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 School of Renewable Natural Resources, 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 two watersheds are situated on relatively flat topography, with few slopes exceeding 10%. Their elevations range from 2,073 to 2,134 m. The most recent timber harvest before the fire removed approximately 45% of the merchantable sawtimber by group selection in the early 1960s. Sixty-five percent of up to 63.5 cm 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 (1-m 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 on the site was re-established 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 severities (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 burn.

Post-Fire Peak Flows

Summer stormflows on the Stermer Ridge watersheds had been uncommon. The highest peak flow measured in a summer stormflow event in the 1972-76 pre-fire period was about 0.003 m^3/sec. However, high-water marks observed on 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 0.205 m^3/sec or 83 times that measured in 1972-1976 period. Peak flow on the watershed subjected to the low-to-medium stand-modifying burn was about one-half less in magnitude but still far in excess of the previous observations. A subsequent rainfall event generated even higher peak flows on the watersheds. On the severely burned watershed, the peak flow following this second event was estimated to be 6.566 m^3/sec or about 2,350 times that measured earlier. This flow represents the highest known post-fire peak flow measured in the montane forest ecosystems of Arizona or, more generally, elsewhere in the southwestern United States.

5. SUMMARY AND CONCLUSIONS

So, the net effect of increased peakflows on watershed systems and aquatic habitat is very much a function of the area burned, watershed characteristics, and the severity of the fire. Small areas in flat terrain subjected to prescribed fires will have little if any effect on water resources, especially if Best Management Practices are utilized.

Flood peakflows after wildfires that burn large areas in steep terrain often produce significant impacts. Peakflow increases of 10 to 100 times are common, but some have been measured as high as 2,300 times pre-fire conditions.

BAER techniques may be able to mitigate some of the impacts of wildfire. However, the ability of these techniques to moderate the impacts of rainfalls that produce extreme peakflow events is limited (Robichaud et al. 2000).

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