Effects of Fire on Water Resources—A Review

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Fire exerts a tremendous influence over forest ecosystems in North America depending on its intensity, duration, and frequency. It is an important natural disturbance that has played a significant role in the development of most forest ecosystems. The "natural" fire that shaped these ecosystems occurred across a continuum that ranged from light burn to catastrophic conflagration. Thus, fire disturbance to riparian and aquatic ecological systems within these forests produces a continuum of effects on water resources.

During most of the twentieth century, foresters focused a lot of attention relative to fire on the multiple resource damages produced by wildfire. Indeed, catastrophic fires produced by natural events (drought, insect outbreaks, lightning) did result in serious impairment to water resources. In the past decade, forest land 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. Thus the impact on water resources also occurs on a continuum. Our ability to state and describe these impacts is a function of the scientific information obtained from a limited range of fires. Obviously, fires and water 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. 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 can range from 50 to 1,000°C. Rates of spread can vary from 1 m in 2 weeks (peat fire) to 6–7 km/hr (large wildfire). Heat yields range from 2 to 2,000 BTU/kg, and fuels grade 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.

Watersheds are used as the basic unit of measure for ecosystem analysis since water is the main transport mechanism that integrates ecosystem processes. Watersheds function on all time and spatial scales. They are also a focus for important human activities (water supply, recreation, resource production). An important part of understanding the impacts of fire on water resources is to comprehend the processes involved. A lot of information has been incorporated here to describe the range of impacts. Since fire is a continuum and data are scarce for some portions of this continuum, not all situations will be adequately described. Therefore, understanding of the processes is a key factor in successful interpretation of the effects of prescribed fires and wildfires on water resources.

Watershed condition, or the ability of a watershed system to receive and process precipitation without ecosystem degradation, is a good predictor of the potential impacts of fire on water resources. The surface cover of a watershed consists of organic forest floor (thin to thick), vegetation (variable cover), bare soil, or rock. Fire can destroy the organic forest floor and vegetation, and alter the infiltration and percolation capacity of bare soil. In some soil-vegetation complexes, water repellency can develop and greatly reduce water infiltration

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(DeBano 1971). This alters watershed (hydrologic) condition, with erosion increasing as watershed condition goes from good to poor.

Water Quantity

Fires affect the quantity of water in a forest ecosystem by affecting key water cycle processes. Fires can reduce interception, thereby reducing moisture storage, increasing water yields, and creating greater runoff with smaller storms. Burning the 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. Burning off 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. Fires alter baseflow and increase stormflow volume and response. Watershed response to storm events is greater with shortened time to peakflow and susceptibility to flash floods is greater. Fires increase snow accumulation and melt in burns of less than 4 ha, but reduce snowpacks where burns exceed 4 ha.

Total Yields

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 magnitude of measured water yield increases the first year after a fire disturbance and can vary greatly at one location or between locations depending on fire intensity, climate, precipitation, geology, soils, watershed aspect, tree species, and 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 disturbances decline as both woody and herbaceous vegetation regrow. This recovery period can range from a few years to decades.

Most of the water yield information deals with the effects of harvesting. Water yield can increase 0–126 percent from harvesting (Neary and Hornbeck 1994). Water yield increases from prescribed fires and wildfires are shown in Table 1. Increases in water yield are highly variable, but generally are greater in regions with high ET.

Baseflows

Baseflows are important in maintaining perennial flow through the year. They are critical for aquatic species (no water, no life). Baseflows can increase if the watershed condition remains good (when infiltration rates are adequate). If the watershed condition deteriorates and more precipitation leaves as surface runoff, baseflows will decrease. In extreme conditions, perennial streams become ephemeral.

Surface runoff (overland flow) occurs when the rain intensity or snowmelt rate exceeds infiltration capacity. It frequently occurs on rock, compacted soils, shallow soils, water repellent soils (after fires), and roads. Overland flow that is 1 percent of rainfall in undisturbed forests can increase to 15–40 percent after fires.

Stormflows, Peak Discharges, and Response Times

The effects of forest disturbance on storm peakflows are highly variable and complex. They can produce some of the most profound impacts that forest managers have to consider. Anderson et al. (1976) offer a good review of peakflow response to disturbance. Peakflows after forest cutting can decrease 66 percent or increase 100 percent depending on location, the percent of the watershed cut, and season (Table 2). Most studies show increases in peakflows of 9–100 percent. The study with an average of 100 percent after clearcutting ranged from -19 to +250 percent for individual storms. An analysis for the Pacific Northwest indicated that if 1 percent of large watersheds were clearcut, peakflows for 100-year floods could increase 6 percent, and annual floods would increase 20 percent. There has been some concern that increases in annual flood peaks of 20+ percent could lead to channel instability and degradation.

Fire has similar to larger effects on peakflows. The Tillamook Burn in 1933 in Oregon increased the total annual flow of two watersheds by 9

Table 1. Increased Water Yield from Burned Watersheds.

Location	WS Condition	Area (ha)	PPT (mm)	Runoff (mm/yr)	Recovery (yrs)	References
S. Carolina	Loblolly Pine		1390			Van Lear, Douglass,
	Control	2		124		Cox and Augspurger 1985
	Understory Burn	2		180	2	
	Burn + Harvest	2		217	2	
Texas	Juniper\Grass		660			Wright, Churchill and
	Control	<1		2		Stevens 1982
	Burned	<1		25	5	
	Burned, Seeded	<1		10	2	
Arizona	Chaparral		740			Davis 1984
	Control	28		64		
	Burned	33		156	>11	
Arizona	Chaparral		585			Hibbert, Davis and
	Control	39		82		Knipe 1982
	Wildfire	39		130	?	
Arizona	Chaparral		655			Hibbert 1971
	Control	19		0		
	Wildfire	19		124	9+	
	Control	39		19		
	Wildfire	39		289	9+	
Arizona	Pinyon-Juniper		480			Hibbert, Davis and
	Control	5		34		Knipe 1982
	Burned	5		39	5	
	Control	5		43		
	Herbicide	5		56	5+	
Arizona	Pinyon-Juniper		482			Clary, Baker, O'Connell,
	Control	134		20		Johnson, Jr., and
	Slash Burned	134		11	4	Campbell 1974
	Control	147		18		
	Herbicide	147		28	4+	
Washington	Pine & Doug-fir		580			Helvey 1980
	Control (preburn)	517		221		
	Wildfire (postburn)	517		314		

percent and increased the annual peakflow by 45 percent. A 127 ha wildfire in Arizona increased summer peakflows by 500–1500 percent, but had no effect on winter peakflows. Another wildfire in Arizona produce a peakflow 58 times greater than an unburned watershed during record autumn rainfalls. Watersheds in the Southwest are much more prone to these enormous peakflow responses due to climatic and soil conditions. Studies have shown both increases (+35%) and decreases (-50%) in snowmelt peakflows.

Another concern is the timing of stormflows or response time. Burned watersheds respond to rainfall faster, producing more flash floods. Hydrophobic and bare soils, and 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. As indicated in Table 2, the Southwest is particularly vulnerable to changes in peakflow response time and volume. Another aspect of this is the fact that recovery times can range from years to many decades.

Table 2. Effects of cutting and fire on peak flows (from Anderson et al. 1976).

Location	Treatment	Peakflow Change (%)	
N. Carolina	Clearcut	+9	
W. Virginia	86% Cut	+21	
	Clearcut	+100	
New Hampshire	Clearcut	+100	(-19 to +250%)
New Hampshire	Clearcut	+35	(Snowmelt)
		-66	(Summer)
Oregon	Clearcut	+90	(Fall storms)
		+28	(Winter storms)
Oregon	Clearcut, Burned	+30	
	Clearcut, Burned (50%)	+11	
Oregon	Wildfire	+45	
Arizona	Wildfire	+500	(Summer Flows)
		+1500	(Summer Flows)
		0	(Winter Flows)
Arizona	Wildfire	+5800	(Fall storms)
Colorado	Clearcut, Burned	-50	
N. Carolina	Prescribed Fire	0	

Water Quality

Erosion

The main features of fires that affect erosion are wildfires (more intense and of greater area than prescribed fires), fireline construction, temporary roads, watershed rehabilitation activities, and increased storm peakflows. Soil loss can take the form of sheet, rill, or gully erosion. Fire-associated debris avalanches are a form of mass wasting that delivers sediment directly to streams in large quantities.

Rotational slumps close to channels can also be sources of sediment. These are mostly associated with water repellency conditions. Chaparral vegetation in the Southwest constitutes a high hazard for debris avalanches.

A stable stream channel reflects a dynamic equilibrium between incoming and outgoing sediment. Increased peakflows after fires can alter this equilibrium by transporting additional sediment into channels (aggradation) and by increasing peakflows that result in channel erosion (degradation).

Sediment Yields

Sediment yields from prescribed burns and wildfires are shown in Tables 3a and 3b. Wildfires generally produce higher sediment yields than other types of disturbances. Slope definitely aggravates sediment losses. After fires, turbidity can increase due to the suspension of ash and soil particles from silt to clay sized in streamflow. Turbidity is an important water quality parameter since high turbidity reduces municipal water quality, and can adversely affect fish and other aquatic organisms. Extra coarse sediments (sand, gravel, boulders) transported off of burned areas or as a result of increased storm peakflows can adversely affect aquatic habitat, recreation areas, and reservoirs. Deposition of coarse sediments destroys habitat and fills in lakes or reservoirs.

Anions–Cations

Undisturbed forests usually have tight cycles for major cations and anions, resulting in low concentrations in streams. Disturbances such as cutting, fires, and insect outbreaks interrupt or terminate uptake by vegetation and speed up mineral weathering, element mineralization, microbial activity, nitrification, and decomposition. These processes result in the increased concentration of inorganic ions in soil solution and leaching to streams via subsurface flow.

Nutrients carried to streams can increase the growth of aquatic plants, reduce the potability of water supplies, and produce toxic effects. Anions like phosphate and cations such as calcium and potassium can be exported from watersheds at 10 times their normal rate immediately after severe disturbances, but don't significantly alter water quality.

Most of the attention relative to water quality after fires focuses on nitrate nitrogen (NO_3-N) because it is highly mobile. Concentrations exceeding 10 mg/L (water quality standard) can cause methemoglobanemia in infants. High NO_3-N levels in conjunction with phosphorus can also cause eutrophication of lakes and streams. Most studies of forest disturbances show increases in NO_3-N (Table 4).

Fire Retardant

Ammonium-based fire retardants (diammonium phosphate, monoammonium phosphate, ammonium sulfate, or ammonium polyphos-

Table 3a. Sediment losses the first year after prescribed burns and wildfires.

Location	WS Condition	PPT (mm/yr)	Sediment Loss 1st Year (Mg/ha)	References
Texas	Juniper\Grass	660		Wright, Churchill and Stevens 1982
	Control		0.060	
	Burned (R = 3 yr)		15.000	
	Burned, Seeded (R = 1 yr)		3.000	
Montana	Larch, Douglas-fir			Debyle and Packer 1972
	Control		<0.001	
	Slash Burned		0.150	
Arizona	Chaparral			Glendening, Pase and Ingebo 1961
	Control		0.175	
	Wildfire		204.000	
California	Ponderosa Pine			Biswell and Schultz 1965
	Control		<0.001	
	Understory Burn		<0.001	
California	Chaparral			Clary, Baker, O'Connell, Johnsen, Jr., and Campbell 1974
	Control		5.530	
	Wildfire		55.300	
Arizona	Ponderosa Pine			Campbell, Baker and Pfolliott 1977
	Control		0.003	
	Wildfire		1.254	
Mississippi	Scrub Oak	1620		Meginnis 1935
	Control		0.056	
	Burned		0.739	
Oklahoma	Mixed Hardwoods	777		Daniel, Elwell and Cox 1943
	Control		0.022	
	Annual Burning		0.246	
N. Carolina	Southern Hardwoods	1190		Copley 1944
	Control		0.004	
	Semi-annual Burn		6.899	
Texas	Loblolly Pine	1040		Pope, Archer, Johnson et al. 1946
	Control		0.112	
	Annual Burning		0.806	
Texas	Loblolly Pine	1040		Ferguson 1957
	Control		0.224	
	Single Burn		0.470	

Table 3b. Sediment losses the first year after fires.

Location	WS Condition	PPT (mm/yr)	Sediment Loss 1st Year (Mg/ha)	References
Mississippi	Scrub Oak	1650		Ursic 1970
	Control		0.470	
	Burned (R = 3 yr)		1.142	
California	Chaparral	950		Wells, II 1981
	Control		0.043	
	Wildfire (R = 3 yr)		28.605	
Arizona	Chaparral	635		Pase and Lindenmuth, Jr. 1971
	Control		0.000	
	Control Burn		3.778	
Arizona	Chaparral	585		Pase and Ingebo 1965
	Control		0.096	
	Wildfire (R = 4 yr)		28.694	
	Wildfire, grass/ herbicide (R = 4)		66.151	
Arizona	Mixed Conifer	635		Hendricks and Johnson 1944
	Control		<0.001	
	Wildfire, 43% slope		71.680	
	Wildfire, 66% Slope		201.600	
	Wildfire, 78% Slope		369.600	
S. Carolina	Loblolly Pine	1390		Van Lear, Douglass, Cox and Augspurger 1985
	Control		0.027	
	Understory Burn (R = 2)		0.042	
	Burn, Cut (R = 2)		0.151	
Arkansas	Shortleaf Pine	1317		Miller, Beasley and Lawson 1988
	Control		0.036	
	Cut, Slash Burn		0.237	
Washington	Mixed Conifer	1475		Helvey 1980
	Control		0.028	
	Wildfire		2.353	
New Zealand	Native Podocarps	2610		O'Loughlin, Rowe and Pearce 1980
	Control		0.429	
	Cut, 20m Buffer, Burn		0.611	
	Cut, No Buffer, Burn		3.432	

Table 4. Effect of forest disturbances on maximum NO_3-N levels in streamflow (from Neary and Hornbeck 1994; and Neary and Michael in press).

Location	Forest Type	Treatment	Maximum NO_3-N (mg/L)
1. Cutting			
New Hampshire	Hardwoods	Clearcut	6.1
West Virginia	Hardwoods	Clearcut	1.4
North Carolina	Hardwoods	Clearcut	0.2
Oregon	Douglas-fir	Clearcut	2.1
2. Herbicides			
New Hampshire	Hardwoods	Cut, Herbicide	17.8
North Carolina	Hardwoods	Cut, Herbicide	0.7
Georgia	Pine\Hrdwds	Herbicide, Cut	5.3
Arizona	Chaparral	Herbicide	15.3
3. Fires			
Oregon	Douglas-fir	Cut, Burn	0.6
Arizona	Chaparral	Herbicide, Burn	18.4
Arizona	Chaparral	Prescribed Fire	12.0

Table 5. Temperature increases resulting from cutting and fire.

Location and Treatment	Buffer Strip	Temperature Increase (°F)	Reference
Oregon: Clearcut	Yes: 15-30 m	14m	Pase and Ingebo 1965
Pennsylvania: Clearcut	Yes: 30 m	3m	Pase and Lindenmuth, Jr. 1971
Oregon: Patch Cut	Yes: ?? m	0	Pope, Archer, Johnson et al. 1946
Clearcut	No	30d	
Oregon: Clearcut, Burn	No	13sm	Ursic 1970
Washington: Wildfire	No	10sm	Van Lear, Douglass, Cox and Augspurger 1985

sm = summer mean temperature
m = mean temperature
d = daily temperature

phate) play an important role in protecting forest resources from destructive wildfires. However their use can affect water quality, producing short-term mortality in some aquatic organisms. For aquatic organisms there is a tradeoff that needs to be considered: Fire and heat can be more destructive to aquatic resources in both the short and long term.

The main chemical of concern in streams 24 hrs after a retardant drop is ammonia nitrogen (NH_3^+ NH_4^+). Non-ionized ammonia (NH_3) is the principal toxic component to aquatic species. The distance downstream at which potentially toxic conditions persist depends on stream volume, the number of retardant drops, and the orientation of drops to the stream's long axis. Concentrations of $NH_3 + NH_4^+$ can reach 200–300 mg/L within 50–100 m below drop points. Under the right concentrations, toxic levels may persist for over 1,000 m of stream channel.

Light and Temperature Effects of Fire on Aquatic Habitat and Biota

Large fires can function like clearcuts in raising stream temperatures due to the direct heating of the water surface; increases of 0–30°F have been measured (Table 5). The two main concerns are reduction in the concentrations of dissolved oxygen and increased aquatic plant growth.

The recruitment of coarse woody debris into streams usually increases immediately after wildfires. This has a positive effect on fish habitat in the short term, but long-term inputs can be disruptive. Prescribed fires generally do not significantly affect coarse woody debris dynamics.

Fish Spawning Habitat

The main impact here is with sediment deposition in spawning gravels. Fine sediments released by fires (primarily wildfires) can clog interstitial spaces and reduce hatching success. Large-scale shifting of bedloads can also impact fish habitat.

Summary and Conclusions

Fires in forest and range ecosystems have a wide range of effects depending on the intensity and resultant hydrologic events. Wildfires definitely produce the largest effects, as they tend to be more intense and cover larger areas. The Southwest has recorded some of the largest changes in streamflow, peakflow, total water yield, and water quality due to the steep topography, the intense precipitation events of the region, and the nature of its soils. Although a lot of information exists about the effects of fires on water resources, efforts need to be made to put this information into a systematic context that can be used for wildland management purposes.

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