

WATER QUALITY IMPACTS OF FOREST FIRES

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This paper is concerned with the effects of forest fires on water quality, especially surface water quantity. The topic is important since surface water constitutes the main source of water for most domestic, industrial and commercial uses in the United States. The bulk of the surface water is the product of runoff from precipitation that falls as snow or rain on our forested and rangeland watersheds. In many areas such as the arid and semi-arid Southwest, the vegetation in these watersheds is dry and susceptible to wildfires. Oftentimes, fire in the form of prescribed burning is used to protect these areas from wildfire. However, such fire suppressions have resulted in overcrowded and dense vegetation and the production of abundant fuels in watersheds. Such a situation and the frequently recurring drought and extensive insect infestation have most forest systems susceptible to catastrophic fires that scorched many of the Nation's forests, rangelands, parks and other large-scale real estate properties (Neary et al. 2008, Lutz et al. 2009, Stein et al. 2013).

In 2013, there were a total of 9,230 lightning started fires in the United States burning 3,057,566 acres. In the same year, there were 38,349 human-caused fires that burned 1,261,980 acres. This made the total acreage burned by the two types of fires in 2013 to be 4,319,546 acres (National Interagency Fire Center 2014). Such fires accounted for \$13.7 billion in total economic losses and \$7.9 billion in insured losses from 2000 through 2011 in the United States (Haldane 2013, International Association of Wildland Fire 2013). These burns also have tremendous effects on the characteristics of water-producing watersheds and the quality of the water coming out of them. This paper discusses the effects of wildland fires on water quality and suggests ways of managing fire-prone forested water source areas to prevent their degradation from wildland fires. The paper uses information from recently occurred catastrophic fires in Arizona to demonstrate the effects of wildland fires on water quality.

GENERAL WILDFIRE EFFECTS

In the past few years, the western part of the United States has seen dramatic increases in the number and intensity of wildfires causing enormous damages to forests, rangelands and other rural areas of Arizona and the Southwest. In the year 2013 alone, for example, five federal agencies: the Bureau of Land Management, the Bureau of Indian

Affairs, the Fish and Wildlife Service, the National Park Service and the Forest Service together spent \$1,740,934,000 to suppress wildfires nation-wide. The same activity cost the five agencies \$1,902,446,000 in 2012 and \$1,733,168,000 in 2011 (National Interagency Fire Center 2014). These costs, though very large, do not include any monetary and material expenditure by other federal, state or local governmental agencies and private sources. State land departments, rural and urban communities' fire fighters and land management entities also spend substantial amounts of money and materials to suppress wildfires at local levels.

There have been very large fires close to home in Arizona recently that cost the State very much in terms of financial, environmental and other valuable resources. In terms of smallest to largest, the three biggest fires in Arizona are the Cave Creek complex, the Rodeo-Chediski, and the Wallow fires. June 2005, the Cave Creek Complex fire, burned 248,310 acres of forest, pasture land and private property all over central Arizona. That fire cost \$16,471,000 to suppress it. Before that, in 2002, there was the Rodeo Chediski fire, which burned 468,638 acres and destroyed 491 structures in the White Mountain area of Arizona. That fire was a part of 6.7 million acres of forest and wildlife habitat area that burned in the USA in that year. More recently, in 2011, we had the Wallow, which burned 535,039 acre, destroyed 72 buildings and hurt 16 people mainly on the Apache Sitgreaves National Forest in Apache, Greenlee, Graham and Navajo counties in Arizona and Catron County in New Mexico. We will briefly discuss the Rodeo-Chediski and Wallow fires as examples of the effect of fire on water quality later in this paper. In the mean time, we note that such big fires have many damaging effects, some immediate and others delayed, on the environment. The effects may also have short term and/or long term durations. At the time of burning, numerous valuable land resources such as timber, wildlife and wildlife habitat, understory vegetation, soil and soil chemicals, historical artifacts, residential homes and other structures are either immediately damaged, or completely destroyed. The delayed effects include numerous post fire environmental degradations such as loss of vegetation cover that leaves the land exposed to impacts from rainfall, runoff, wind and solar radiation resulting in soil hydrophobicity (DeBano et al. 1998), flooding, soil

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erosion and off-site downstream degradation of streams, lakes and reservoirs (Morgan and Erickson 1995, Veenhuis 2002). Knowledge and good understanding of these possibilities is important for developing appropriate forest and other landscape management to minimize the effects of forest fires on water quality.

FOREST FIRE EFFECTS ON WATER QUALITY AND FLOODING

The main concerns for hydrologists and water resources managers with wildfires are their impacts on water quality and peak flow. The hydrologic influence of vegetation cover ranges from intercepting and reducing the amount of precipitation reaching the ground to enhancing the rate of infiltration and thereby decreasing the amount and rate of surface flow. Wildfire, on the other hand, not only burns vegetation cover but also destroys forest floor material leaving the ground bare and sometimes with hydrophobic soils that slow infiltration rate and allow for more and faster surface water movement (DeBano 1981, Morgan and Rickson 1995, Zwolinski 2000). However, soil hydrophobicity disappears when the temperature of burned areas reaches 300°C. For most fire burns, soil temperatures remain below this level leading to hydrophobicity and subsequent increase in flowing water (Dlapa et al. 2006). Apart from decreased infiltration and faster surface flow, the other major effect of forest fires is on water quality.

Factors that Affect Water Quality

The factors that affect the type and severity of post-forest fire water quality are complex and vary significantly from place to place depending on effective precipitation, soil and vegetation cover characteristics as well as the geologic, topographic, and fire severity conditions in the area (Robichaud et al. 2000). The water quality concerns may be grouped into physical and chemical related prob-

lems. The physical water quality and associated problems that follow forest fires include erosion and sediment yield, turbidity, flooding, and increased temperature. The chemical water quality problems that may arise after forest fire may consist of increased production of macronutrients, micronutrients, basic and acidic ions and decreased oxygen level. Some of these chemicals come from the disturbed and bare ground and others are produced from the burned plant material. Increases in stream flow also changes with time following fire disturbance. In general, Hibbert (1971) and Hibbert et al. (1982) found that first-year water yield from various burned watersheds in Arizona increases from as low as 12% to one exceeding 1,400% of normal flow.

The effects of fires on storm peak flows are highly variable with the magnitude and variability of peak flows being dependent on many factors such as topography, soil and vegetation cover characteristics, fire severity and precipitation intensity. Peak flows over burned areas in the Southwest commonly increase in magnitude from 500 to 9,600% (see Table 1) of that occurring on unburned areas during the summer months when highly intensive monsoonal thunderstorms are the norm in the area. The increase in Salt River stream peak flow of 4,000% following the year 2002 Rodeo Chediski fire (see Fig. 1) and those of the 2011 Wallow fire are very significant and fall in the above range. Others have also found that the increase could even be higher as the value from a burned chaparral watershed in Table 1 shows. The increase in peak flow from burned chaparral watersheds can reach as much as 45,000%. Again, these results indicate the need for careful management of southwestern watersheds to minimize the occurrence of severe wildfires that upset the normal quality and quantity of water in and from forested areas.

Table 1. Percent increase in peak flow following forest burn at different locations.

Location	Vegetation type	Percent increase	References
Eastern Oregon	Ponderosa pine	45	Anderson et al. 1976
Central Arizona	Mixed conifer	500-1,500	Rich 1962
Central Arizona	Ponderosa pine	9,600	Anderson et al. 1976
Cape region of South Africa	Monterrey pine	290	Scott 1993
Southwestern U.S.	Chaparral	200-45,000	Sinclair and Hamilton 1955; Glendening et al. 1961
Northern Arizona	Ponderosa pine	200-5,000	Leao 2005

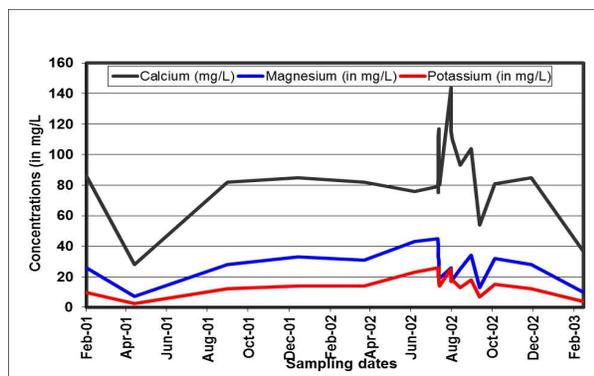


Figure 1. Macronutrient concentrations, Ca, Mg and K after Rodeo-Chediski Fire in the Salt River at the entrance to Roosevelt Lake.

Forest Fire Impacts on Water Quality

The level of influence of wildfires on water quality can be substantial depending on the severity of the wildfire, the nature of vegetation cover, and the physical and chemical characteristics of the burned area (DeBano et al. 1998). Large and fast stream flows from burned areas can pick and transport large amounts of debris, sediment and chemicals that significantly affect the quality and use of water downstream. Also, wildfires interrupt or terminate nutrient uptake, increase mineralization and mineral weathering. These were the cases in the recent three largest fires in Arizona. One of them, the Cave Creek Complex fire of 2005 burned 248,310 acres of forest, pastures and private property, generated huge amounts of sediment load in streams and cost \$16,471,000 to suppress it. The largest fire in Arizona history, the Wallow, which burned 535,039 acres in northeastern Arizona and parts of New Mexico in 2011, left a lot of destruction and waste on its way. The most obvious environmental effects of the fire were in the form of bedload and suspended sediments in lakes, reservoirs and stream flows that affected fish and other wildlife. Reservoirs such as Nelson, River and Luna received large ash flows from severely burned areas resulting in significant fish kill. Certain lakes such as Helsey Lake and Ackre Lake were filled with sediment and suffered the most with all of their fish population dying. Also, a number of Apache trout and Gila trout streams suffered significantly fish kill. These streams include South Fork of the Little Colorado River, Bear Wallow Creek, Hannagan Creek, KP Creek, Raspberry Creek and upper Coleman Creek. However, the effects were highly variable with some areas having the greatest impacts on fish population from ash flows and flooding following the Wallow fire.

The most destructive of the three big fires was the Rodeo-Chediski fire of 2002. That fire burned 468,638 acres of forest land, and destroyed 491 structures in the White Mountain area of Arizona. In addition, the fire had other major environmental

effects in the form of physical and chemical problems that affect downstream water quality. This was determined by looking at various water quality parameters measured at the Salt River entrance to Roosevelt Lake. Figures 1 and 2 show significant increases in the concentration of the major macronutrients of calcium, magnesium and potassium (Fig. 1) and sulfate, phosphorus, and total nitrogen (Fig. 2) in Salt River water following the Rodeo-Chediski fire. Though, there were increases in the calcium and sulfur concentrations following the Fire, the values remain less than half of the U.S. EPA standard concentrations for calcium and sulfur, whereas those for magnesium, potassium, phosphorus and total nitrogen rose about 2, 5, 390, and 22 times, respectively.

Figure 3 shows the concentrations of the hazardous chemicals of arsenic, copper, iron and lead in the Salt River where it enters Lake Roosevelt. The values are high and dangerous, consisting of about 6,850%, 300%, 3,000%, and 460% of the U.S. Environmental Protection Agency standards for arsenic, copper, iron, and lead, respectively. Figure 4 represents the adverse levels of the physical factors of flooding, turbidity, temperature and specific conductivity on the Salt River water following the Rodeo-Chediski fire. As shown in the figure, the flood magnitude in the Salt River flow entering Lake Roosevelt increased by 6,000% following the Rodeo-Chediski fire. Turbidity and specific conductivity measurements at the same time increased by about 1,500,000% and 422% of the U.S. EPA standards, respectively, while temperature rose to an uncomfortably high level of 29°C. The post-Rodeo-Chediski water quality parameters' values are shown in column 2 of Table 2. The table also compares those values with the World Health Organization (WHO) and U.S. EPA drinking water standards values, shown under columns 3 and 4, respectively.

To summarize, wildfire can have devastating effects on water quality that affect water dependent living things and the physical environment. This is demonstrated in the post Rodeo-Chediski chemical concentrations and physical water quality levels indicated in column 2 of Table 2. Most of these values when compared with those of drinking water standards in columns 3 and 4 are very high and dangerous to aquatic life and other living things. For example, the turbidity value of 51,000 NTU, if persisted would make the reservoir water nontransparent and practically too dark for any limnetic and deeper dwelling aquatic organisms to function properly. Likewise, the high temperature value as well as the highly elevated presence of salts and other chemicals could make the water unsuitable for many organisms for some time like those of Lakes Helsey and Ackre in which all fish died following the Wallow fire. The very high macro- and micro-nutrient values could also lead to increased algal

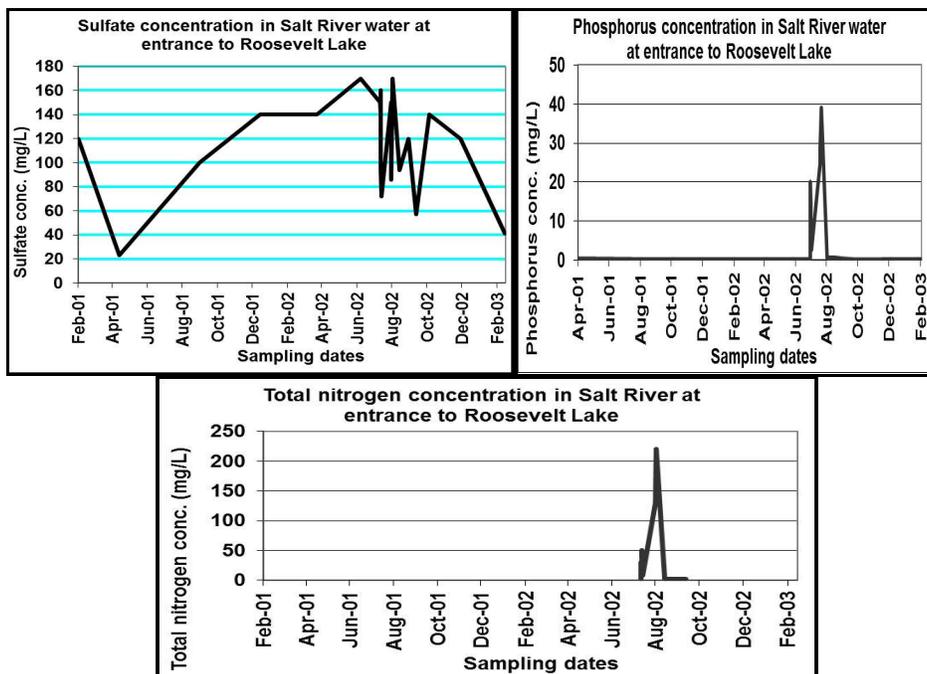


Figure 2. Macronutrient concentrations of S, P and N after Rodeo-Chediski Fire in the Salt River at the entrance to Roosevelt Lake.

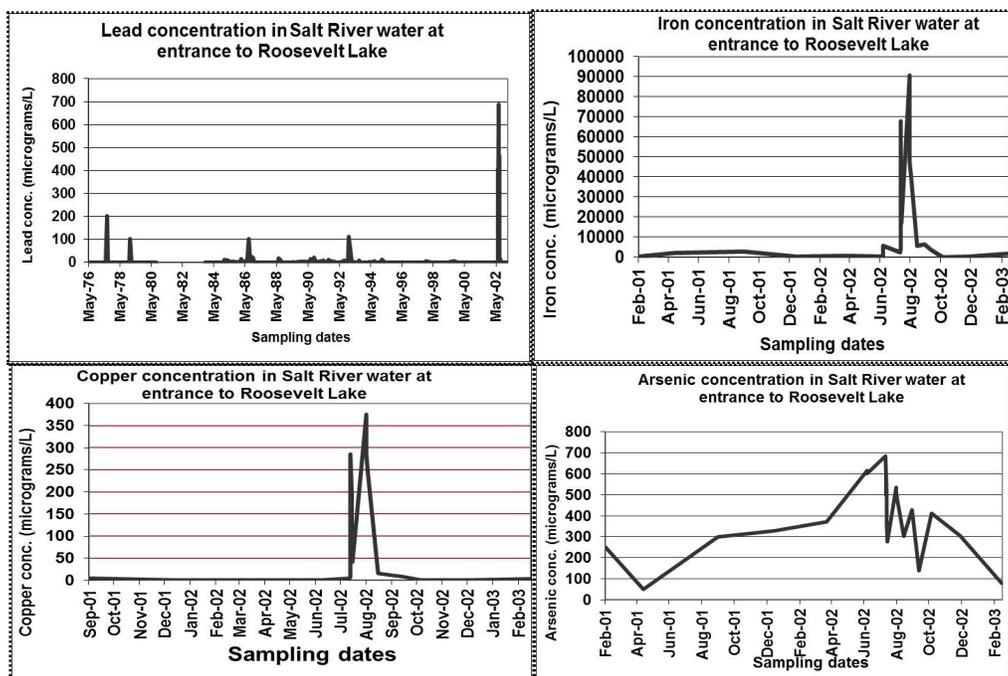


Figure 3. Hazardous mineral concentrations after Rodeo-Chediski Fire in the Salt River at the entrance to Roosevelt Lake.

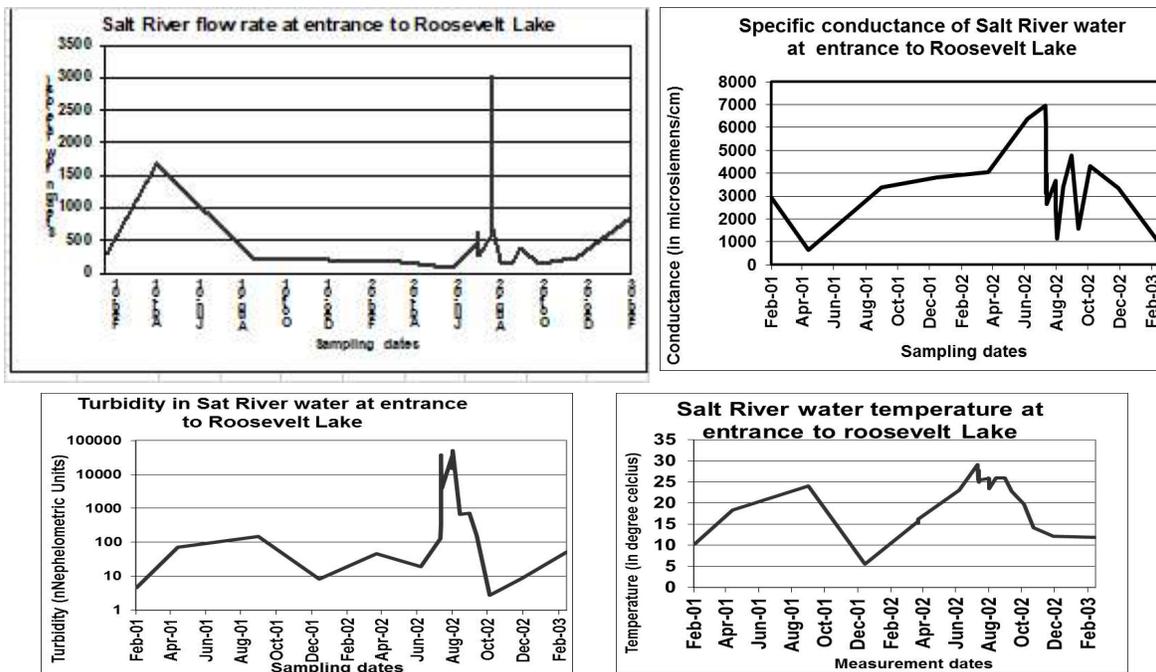


Figure 4. Flooding and physical water quality effects of the Rodeo-Chediski Fire in the Salt River at the entrance to Roosevelt Lake.

growth and eutrophication of the water making it unfit for drinking and aquatic fish habitat. Luckily, the serious effect of the fire on the various water quality parameters did not persist for long (Paterson et al. 2002, Wondzell et al. 2003). This is demonstrated in Figures 1 through 4 in which the highly elevated levels of the various Salt River water quality parameters rapidly decreasing shortly after the burn period.

CONCLUSION

The impacts of wildfires on peak flow and water quality can vary very much and become highly significant. Because there are not sufficient amounts of vegetation cover left on watersheds after wildfire burns, and also because soils become hydrophobic soon after most forest fires, most precipitation that falls on such areas is readily converted to surface flow, which moves downstream with little or no difficulty. Such flows may be huge in amount, have high velocities and be very forceful to severely disturb and damage watersheds and stream channels, and then carry large quantities of sediment and other chemical contaminants downstream. Wildfires can also interrupt or terminate nutrient uptake, increase mineralization and lead to mineral weathering. Increased temperatures decreased dissolved oxygen and introduction of nutrients and toxic materials into water bodies can cause eutrophication and destroy aquatic life. Hence it is important that foresters, other land resources managers and any interested parties make all efforts to minimize the

occurrence of damaging fires. This can be done through forest thinning and appropriate harvesting methods and levels, prescribed fire and paying careful attention to possible occurrences of fires and other harmful forest disturbances and dealing with them diligently before the problems become out of control. This requires well-educated and highly insightful decision makers, availability of necessary rules and regulations, adequate budget and skilled workers to proactively prevent forest fires and control them once they occur. Such proper management of forested watersheds should prevent and/or minimize forest fires that can lead to catastrophic flooding and result in major water quality problems. Preventing forest fires is also important as returning burned sites is extremely expensive and takes a very long time to restore them to pre-fire conditions.

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Table 2. Rodeo-Chediski fire effects on water quality measured in Salt River at the entrance to Roosevelt Lake, and WHO and U.S. EPA water quality standards.

Parameter	Post-fire water quality levels	Guidelines for Drinking Water Quality	
		World Health Organization	U.S. Environmental Protection Agency
1	2	3	4
Arsenic	0.685 mg/L	0.01 mg/L	0.01 mg/L
Bicarbonate	312 mg/L	NI**	380 mg/L
Calcium	144mg/L	NI	380 mg/L
Chloride	2110 mg/L	(>250 mg/L)	250 mg/L*
Copper	0.375 mg/L	2 mg/L	1.3 mg/L
Iron	90 mg/L	2 mg/L	0.3 mg/L*
Lead	0.690 mg/L	0.010 mg/L	0.015 mg/L
Magnesium	45 mg/L		20 mg/L *
Mercury	0.7 mg/L	0.006 mg/L	0.002 mg/L
Phosphorus	39 mg/	NI	0.1 mg/L*
Potassium	26 mg/L	NI	5 mg/L
Sulfate	170 mg/L	(>250 mg/L)	250 mg/L
Total nitrogen	220 mg/L	NI	10 mg/L *
Dissolved oxygen	7.4 mg/L	NI	>5 mg/L *
Suspended sediment	25800 mg/L	>600 mg/L (TDS) ****	500 mg/L (TDS) *
Spec. conductivity	6970 μ S/cm	NI	1650 μ S/cm *****
Temperature	29°C	NI	NI
Turbidity	51000 NTU	NI	1 NTU*

*Secondary drinking water standard

**NI = no information

*** TDS=total dissolved solids

***** μ S=microsiemens

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