The Role of Fire in Management of Watershed Responses

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Abstract.—Hydrologic responses of watersheds are strongly related to vegetation and soil disturbances. Many of the storage and transfer components of the global hydrologic cycle are altered by the occurrence of fire. The major effect of fire on the hydrologic functioning of watersheds is the removal of vegetation and litter materials that protect the soil surface. Reductions in interception and evapotranspiration losses, infiltration rates and soil moisture deficits following severe fires result in more water available for surface runoff and subsequent changes in peak discharges, erosion, sedimentation and water quality. Watershed management implications regarding fire severity, wildfire and prescribed burns are discussed.

Introduction

The hydrologic functioning of a watershed depends on its ability to receive, store, and transmit water and is strongly correlated with vegetation and soil disturbances. Fire, which has the potential to significantly alter vegetation and soil properties, can cause a wide variability in watershed hydrologic responses.

During the past several decades resource managers have acquired a better understanding of the role of fire in natural ecosystems, particularly by observing the spectrum of impacts ranging from catastrophic wildfires to carefully executed prescribed burns. The absence of periodic fires in fire-adapted ecosystems has caused substantial changes in fuel accumulations, nutrient cycling, soil moisture distribution and overall watershed productivity. As a result, fires often produce higher intensities and longer durations that result in increased fire severity. With the importance of watershed management continuing into the 21st century and the role of fire becoming better defined, land stewards will need to be more fully aware of these hydrologic responses of watersheds to different fire severities. This paper briefly examines the on-site and downstream impacts of fire on the hydrologic processes on watersheds.

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On-Site Fire Impacts

Interception

Interception of rain or snow by vegetation and litter results in a loss of water for streamflow. The magnitude of interception varies considerably depending on size of vegetation, density, foliage and branching characteristics (Ffolliott and Brooks 1996). A low severity fire that does not change the vegetation interception characteristics will have minimal impact on water yield. However, a severe fire that removes canopy foliage and litter material can result in significant increases in water flow and soil erosion. In situations where overstory vegetation is removed by fire, but some organic material remains to protect the soil surface (analogous to mechanical removal of trees and shrubs) water yields are initially increased and erosion rates remain low. However, the decreased interception allows a greater influx of solar radiation, resulting in removal of water from the site by evaporation and snow sublimation.

Evapotranspiration

Evapotranspiration is a term that combines water evaporation from soils, or standing water surfaces, with water released to the atmosphere by vegetation through transpiration. Watershed managers are interested in evapotranspiration because it represents a loss in the amount of water available for on-site and downstream use. The impacts of fire on this hydrologic process are largely dependent on the degree to which fire alters the vegetation canopy. As already mentioned, removal of interception surfaces, namely foliage, allows more precipitation to reach the soil surface. Also, foliage removal increases water yields because transpiration is reduced. For example, Ffolliott and Thorud (1977) reported that a 5% reduction in evapotranspiration following a burn on a forested watershed in the Southwestern United States resulted in a 30% increase in annual runoff. Increased watershed yields also can result when severe fire removes an existing deep-rooted vegetation type (tree, shrubs) and the site is subsequently occupied by shallow-rooted plant species (grasses). However, on the severely burned sites high rates of erosion occur, particularly the first few years following fire. Also, tree or shrub conversion to grass can often result in increased mass soil movement on steep slopes having shallow soils (Bailey and Rice 1969).

Infiltration

Infiltration is the physical process of water passing through the soil surface into the soil profile. Rates of infiltration are a function of soil texture and porosity, surface organic material and vegetative cover. Direct and indirect effects of fire can alter these parameters depending on fire severity. Minimal impacts are evidenced following fire when intensity and heat output are too low to result in complete litter and duff layer removal. Should a fire be severe enough to expose mineral soil, several conditions can occur to significantly decrease infiltration rates. First, the impact of falling raindrops on bare soil surfaces can lead to physical compaction and reduction in soil porosity. Second, exposure of mineral soil after fire normally implies that organic matter that structurally binds soil particles also has been consumed and that soil structure has collapsed. This results in increased soil bulk densities and decreased pore space (Zwolinski 1971). A third condition following severe fire is the displacement and saltation of soil particles by raindrop impacts and subsequent sealing or plugging of soil pores. These three conditions, often occurring simultaneously, can effectively reduce soil water infiltration. When soil water entry rates are markedly reduced and more water is available to surface runoff, then increased erosion and sedimentation problems are likely to occur.

On watersheds where vegetation produces high amounts of organic substances, i.e., chaparral, a non-wettable or hydrophobic layer formed at the soil surface restricts water infiltration. Heating from severe fires can volatilize the organics in the litter/duff and soil surface layers and, due to temperature gradients, transport these chemicals deeper into the soil profile where condensation and a new hydrophobic layer occur (DeBano 1981). This subsurface condition will impede further downward movement of infiltrated water and cause the saturated, wettable soil perched above the water repellent layer to slide downslope and create large uncontrollable mudslides and debris flows (Wells 1987).

Soil Moisture Storage

When the soil mantle becomes saturated, any further additions of water will result in surface runoff. Soil moisture can be depleted by evaporation and plant root absorption. The wilting point is reached when forces holding water in the soil matrix are balanced by the osmotic gradient drawing water into plant roots. Removal of a high water using vegetation type by a severe fire will reduce transpirational draft and result in a greater quantity of water remaining in soil storage (Tiedemann and Klock 1976). Therefore, a lesser amount of subsequent precipitation and infiltration is needed to bring the soil to its maximum water holding capacity and, ultimately, lead to surface runoff. Fires of lower severity, where vegetation is not drastically altered, will have little of no impact on soil moisture storage.

Snow Accumulation and Melt

Fires influence snow deposition and melt characteristics when openings are established in formerly dense forested overstories. The blackened remains of on-site fuels penetrating through the snowpack can change surface albedo and cause an earlier and more rapid snowmelt and runoff (DeBano, et al. 1998). Openings in vegetation types from fire will have reduced interception loss and allow greater snow accumulation. Solar radiation penetration to the surface under these open conditions also enhances earlier snowmelt and runoff.

Downstream Fire Impacts

Runoff Quantity

In examining the on-site impacts of fire on watershed hydrologic responses, it is apparent that severe fires can alter vegetation and soil characteristics resulting in increased flow volumes. Reductions in interception and evapotranspiration losses, infiltration rates and soil moisture deficits result in more water becoming available for overland flow and subsequent stream runoff. Low, or even moderate, severity fires will elicit runoff increases commensurate with the degree of vegetation and soil alteration.

Peak Flows and Timing

Increased peak flows and earlier runoff patterns have been reported following severe fire (Tiedemann and Klock 1976). This increased runoff results from rapid snowmelt caused by the removal of overstory vegetation and greater solar radiation influx.

Erosion and Sediment

Runoff and erosion are directly related to decreased infiltration, raindrop splash, surface erosion and sediment movement. Accelerated erosion often occurs following high severity fires (DeBano, et al. 1998). Sediment carried from a watershed as a result of erosion is subsequently deposited downstream. The quantity of suspended material is dependent upon soil properties, flow velocities, watershed geomorphology and scour potential of stream channels. Sediment-laden water flows also can result in substantial losses of aquatic organisms and fish habitat.

Water Quality

Water quality refers to the abiotic and biotic substances contained in water and their impacts on a particular use. Watershed managers are particularly concerned with suspended sediments, dissolved chemicals and bacteriological components. Combustion of organic fuels on watersheds by fire results in mineralization and release of chemical nutrients, principally Ca, Mg and K. These elements can increase soil pH by occupying cation exchange sites. Green up of a burned site shortly after fire is primarily due to increased nitrogen availability. Fire also can convert bound organic nitrogen and phosphorus to soluble forms. An indirect effect of increased N and P in streamflow following fire is the potential for eutrophication. This enrichment process promotes increased algal growth and adversely affects the dissolved oxygen content of water.

Management Implications

The major effect of fire on the hydrologic functioning of watersheds is the removal of vegetation and litter materials that protect the soil surface. The quantity of vegetation and litter cover removed determines the magnitude of watershed responses (DeBano, et al 1996). Consequently, fire severity becomes an important parameter for watershed managers to evaluate when assessing post-fire impacts. Although much of the information available on hydrologic responses has been obtained following wildfires, where large changes are readily measured, lower severity fires, i.e., prescribed, show little or no hydrologic impacts (Figure 1). Most prescribed burn plans, other than those for severe fires used to remove undesired vegetation types, ensure that litter / duff material remains on site to protect the soil surface. However, due to the wide variability in fuel loadings and on-site conditions, even prescribed

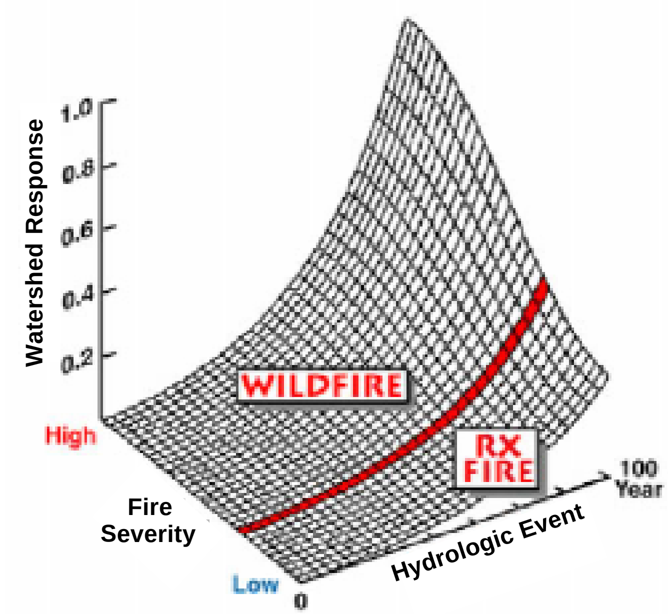

Figure 1. Fire severity continuum (Source: Neary, D. G., M.B. Baker, Jr., L.F. DeBano and P.F. Ffolliott [unpublished]).

fires can be severe enough to create small areas where mineral soil has been exposed.

Watersheds can be managed effectively for water production and other resource values using prescribed fire. Careful application of fire, with attention to maintaining the integrity of on-site vegetation and litter cover, also can reduce fuel loadings and promote positive forest, range and wildlife objectives. However, wildfires that consume large amounts of vegetation and litter can produce substantial increases in surface runoff, peak flows and sediment, even under average precipitation regimes.

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