Hydrologic and Water Quality Effects of Fire[1]

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Abstract.—Prescribed burns usually have minimal hydrologic impact on watersheds because the surface vegetation, litter, and forest floor is only partially burned. Wildfire can, however, have a pronounced effect on basic hydrologic processes, leading to increased sensitivity of the site to eroding forces and to reduced land stability. Fire often causes increased overland flow and greater peak and total discharge, factors responsible for transporting sediment from the site. Fire also causes rapid mineralization and mobilization of nutrients. Because of the natural variability found in forest and range environments in the Southwest, the fire influence continuum, which land managers face in this area, is quite broad.

INTRODUCTION

Water is a valuable resource derived from forests and rangelands, and is also the principal carrier of nutrients through the soil-plant-water-atmospheric continuum. Of all natural resources, water is probably the most sensitive to the disturbance of vegetation and soils on the land surface. Water responses to disturbances include changes in (1) timing and quantity of flow, (2) physical parameters, such as temperature, sediment content, dissolved oxygen, and (3) biological and chemical constituents.

Water yield and stormflow may be increased by burning forest and rangelands. The amount of increase depends on the intensity and severity of burning and the proportion of the watershed burned. Where vegetation is destroyed, interception and evapotranspiration are reduced. Where the organic layers of the forest floor are consumed and mineral soil exposed, infiltration and water storage capacities are reduced. The duration of fire effects ranges from very short periods to many decades, depending on the intensity of the fire itself and rate of vegetation recovery, which is influenced by both natural conditions and remedial measures applied by man.

Occasional fire has always been a natural occurrence in many ecosystems; many existing forest types owe their origin and perpetuation to fire (Stokes and Dieterich 1980). Therefore, what we call normal hydrologic behavior of many forested watersheds already incorporates fire effects.

Prescribed burns are used to attain various timber management objectives and to reduce the risk of insects, disease, and wildfire. These burns are generally made during periods of less intense burning conditions so the damage to the forest floor and understory vegetation is less severe than during intense wildfire. Prescribed burning conditions needed to achieve desired management objectives can, however, be difficult to obtain for the various vegetation and weather conditions found in the Southwest without also causing some adverse effects to the watershed. Burning prescriptions are further complicated by the wide variation in physiographic conditions encountered.

In this review, studies of both prescribed burning and wildfire have been utilized in the assessment of fire effects on the hydrology and water quality from forest and rangeland vegetation types in the Southwest. Although emphasis is intended to be on effects of prescribed burning, often such information was not available. Fire influence in this paper is viewed as a continuum, with effects of prescribed burning at one extreme and wildfire at the other. In a given burning situation, many, if not all, burning conditions will be present to some extent and the final "fire effect" will be an integration of all of them. Therefore, information from situations other than "prescribed burning" is used to estimate possible responses that may be anticipated from burning.

DESCRIPTION OF AREA

As used here, "Southwest" refers to the area between 27° and 37° N. latitude and 103° and 118° W. longitude (Brown 1982). Although this area centers on Arizona and New Mexico, it also includes parts of California, Colorado, Nevada, Texas, Utah, and Mexico (fig. 1). This area supports a range of vegetation that includes major arid and subarid biotic communities.

Vegetation types found in the Southwest, going from lower to higher elevations, are: desert, semidesert grasslands, chaparral, pinyon-juniper, ponderosa pine, and mixed conifer-aspen (fig. 2). Generally, the higher elevation pine and mixed conifer-aspen types are considered high water and low sediment producing areas (Brown et al. 1974, De-

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Bano 1977, Hibbert 1979, Hibbert et al. 1974). At mid-elevations, pinyon-juniper and chaparral cover types produce intermediate amounts of water and sediment. The lower lying semidesert and desert areas produce little water and large amounts of sediment.

Precipitation regimes play a major role in the hydrologic response of different vegetation types to burning in the Southwest. Average annual precipitation ranges from about 30 mm to over 800 mm (fig. 2). About 55% of the annual precipitation in the central mountains of Arizona falls as rain or snow between November and April. Snow, a significant factor in the higher montane conifer communities, seldom occurs below the 900-m level in the arid desertscrub vegetation types. Winter storms may release large amounts of water, but their intensities are usually relatively low. Approximately 35% of the annual precipitation occurs during July, August, and September as local convective storms that can be intense and erratic, and that strongly influence erosion and sedimentation. Water yield is essentially nonexistent below an average annual precipitation of 460 mm except for occasional, local, "flashflood" occurrences derived from locally, intense thunderstorms (Hibbert 1979).

ON-SITE EFFECTS

Hydrologic processes that may be affected by fire include precipitation, interception, infiltration and overland flow, soil water storage, snow accumulation and melt, and surface erosion.

Precipitation Interception

Interception—the process of vegetation interrupting the fall of precipitation onto the soil surface—is important because it reduces raindrop impact at the soil surface and, consequently, detachment of soil particles. Soil erosion proceeds in three steps: detachment, transportation, and deposition (sedimentation). The kinetic energy of a falling raindrop on bare soil is sufficient to kick soil particles 1 meter into the air (Hewlett 1982). Osborn (1954b) showed that 50 mm of rain has the potential to detach and set in motion 179 metric

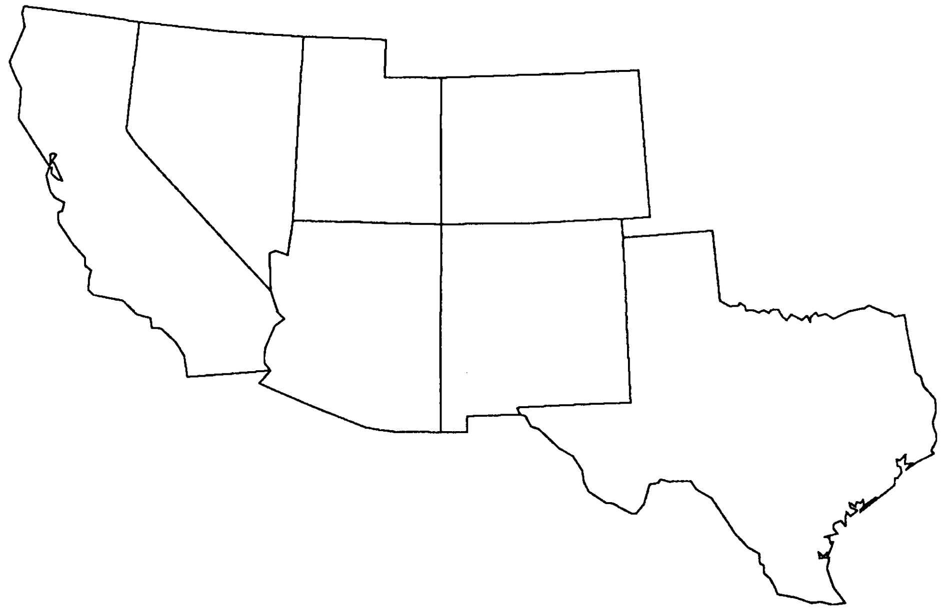

Figure 1.—Biogeographic provinces of the Southwest.

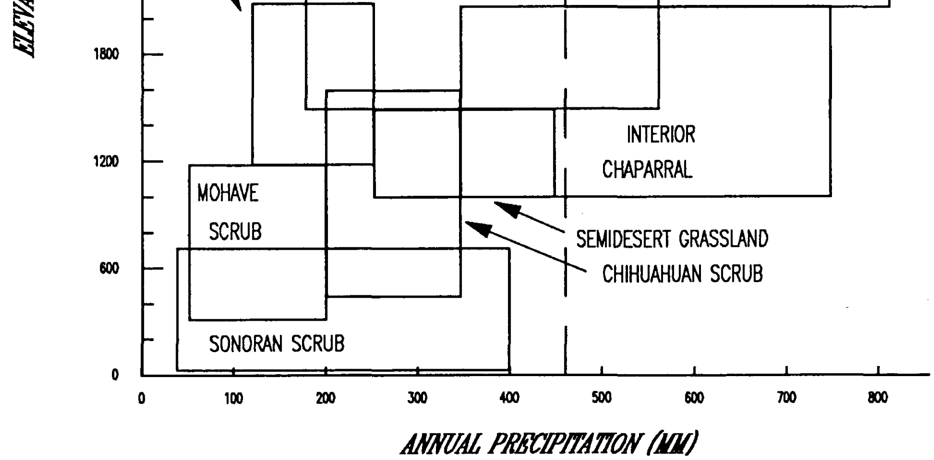

Figure 2.—Elevational-precipitation relationships of biotic communities.

tons of soil material per hectare. The effectiveness of vegetative cover in preventing soil detachment is directly proportional to the amount of cover (Osborn 1954a).

Interception losses during individual rainstorms are a function of interception storage, water stored by plants and the forest floor, and of meteorological conditions, such as precipitation amount, intensity, and duration, and wind speed, during the storm. The percentage of total precipitation lost to interception increases directly with density of vegetation and foliage cover and indirectly with amount of precipitation received and storm duration. Interception losses on undisturbed forest lands during large, flood-producing storms are relatively small, ranging from about 2% to 10%.

The amount of water required to wet vegetation ranges from 0.3 to 2.3 mm for coniferous and hardwood forests (Helvey 1971); for shrubs and grasses it averages 1.3 mm (Zinke 1967). Forest floor interception storage ranges from 2% to 27% of the gross precipitation (Helvey 1971). Zinke (1967) reported that storage values for the forest floor average about 4.1 mm, but other studies indicate the average may be closer to 3.0 mm (Clary and Ffolliott 1969, Garcia and Pase 1967, Kittredge 1955).

Successful prescribed burns in forests consume only part of the forest floor fuels. Prescribed burns do not normally consume canopy material except for some smaller trees in dense stands and possibly occasional scorching of larger trees. In contrast, wildfires often spread through the forest canopy producing an intense fire that not only consumes much of the canopy but also the surface fuels, litter, and forest floor. Thus, prescribed burns have little effect on canopy interception and mainly express their influence by reducing the amount of interception by the lower canopy vegetation and the amount of water storage capacity of the forest floor. Also, because prescribed burns generally produce lower temperatures, they don't have the same effect on the soil properties as wildfires.

In chaparral, differences between prescribed burns and wildfires become smaller because the chaparral canopy carries the fire during both types of burns (DeBano, pers. comm.). There are still some important differences, however, because most prescribed burning is done under marginal or less severe burning conditions when (1) cooler air temperatures and higher humidities prevail, (2) live and dead fuel moistures are high, and (3) wind speeds are low. These conditions often result in a patchy burn, with areas of completely consumed vegetation intermixed with areas partially consumed. Prescribed burns and wildfires in grasslands probably behave much the same way as in chaparral because the canopy (grass cover) also carries the fire in these situations.

Infiltration and Overland Flow

Infiltration may be defined as the amount of water that can move through the soil surface in a given time period. If more water is supplied than can infiltrate, the excess runs off rapidly as overland flow. Some important variables found to affect infiltration under simulated high-intensity rainfall rates (91-127 mm/hr) include: percentage of ground cover, vegetation cover type, soil texture and porosity, and amount of soil organic material, (Dortignac and Love 1961, Meeuwig 1965).

Many of these factors affecting infiltration are adversely affected by fire, resulting in reduced infiltration and increased overland flow (Hendricks and Johnson 1944). Soil organic matter, which is concentrated at or near the soil surface, is directly exposed to heat radiated downward during a fire. Organic matter begins changing chemically when heated to 200°C and is completely destroyed at 450°C (Hosking 1938). Soil organic matter is important for maintaining aggregate stability and soil structure, which affect infiltration and other hydrologic properties of the soil such as water repellency. Fire also indirectly affects microclimate on a site causing greater temperature extremes in both the air and soil (Fowler and Helvey 1978). Such temperature changes can influence soil freezing, soil water depletion, and snowmelt rates which also influence infiltration.

In chaparral vegetation, fire has been shown to create water-repellent layers in the soil (DeBano 1981). Nonwettability increases as intensity of fire increases. These layers create a nonwettable condition that seriously inhibits infiltration and is a major cause of increased overland flow (DeBano 1971, Rice 1974). Although water-repellency problems are most pronounced in chaparral zones, the problem is not confined to this vegetation type.

The effect of fires on runoff is also influenced by burning frequency. Frequent burning can eventually remove most of the protective vegetative cover and, thereby, increase the potential for overland flow.

Prescribed burning.—Prescribed burning probably has its greatest influence, hydrologically, on infiltration and, consequently, on overland flow potential. Because of natural variation in moisture conditions, prescribed burns normally produce a mosaic pattern of consumed organic matter and, consequently, various degrees of influence on water storage capacities and infiltration rates within an area. If properly executed, prescribed burning will not significantly affect, either spatially or temporally, the integrated overland flow and streamflow regime of a watershed.

Overland flow following prescribed burning is directly related to slope steepness and indirectly related to the rate at which disturbed areas are revegetated (Wright et al. 1976).

Vegetation does not usually develop as rapidly or uniformly on steep slopes, as on more moderate slopes.

Light, intense burns can significantly decrease infiltration capacities in the ponderosa pine forest type (Zwolinski 1971). Infiltration data often show a prominent depression after the start of water application caused by soil nonwettability or water repellency. Restoration of the infiltration capacity to near normal often occurs during the winter, however, because of repeated freezing and thawing of the soil. A significant increase in soil bulk density can also be obtained following a heavy burn but not usually after light burning. Removal of organic material probably causes a breakdown in soil structure, resulting in a more compacted surface soil.

Wildfire and slash burning.—Wildfire, as explained, often consumes all or nearly all of the organic matter over extensive areas of a watershed, producing a significant effect on its streamflow regime for a number of years after the fire.

Overland flow on unburned chaparral watersheds rarely exceeds 1% of rainfall and is often nonexistent (Hibbert et al. 1974, Rice 1974). Stormflow increases greatly after wildfire because of increases in surface runoff (overland flow) on severely burned, unprotected, water-repellent soils (Hibbert 1985). In the first year after fire, overland flow has accounted for up to 40% of the rainfall, with the average ranging from 10% to 15% (Rice 1974). Burning in the northern California brush zone normally produces no consistent difference in surface runoff from sparsely covered chamise plots, but runoff may increase by a factor of up to 15 after burning in the denser manzanita, oak, and shrub oak types (Anderson 1949). Postfire recovery is normally rapid, with a decline in severe flooding in 3 years and stormflows in 5 to 10 years (Hibbert 1985).

Water repellency can also develop in sandy textured soils of ponderosa pine ecosystems following wildfire (Campbell et al. 1977). Infiltration rates can be reduced by half (in one example going from 68 to 26 mm per hour), but this situation usually returns to prefire conditions within a matter of years.

Soil Water Storage

In most areas of the United States, the soil mantle is recharged to capacity or near capacity during the springtime. At the start of the growing season, transpiration proceeds rapidly using the readily available water stored in the soil. As the season progresses, water stored in the soil is diminished. Water deficits, that usually exist in the soil by the fall, are subsequently reduced through the winter and early spring. Vegetation removal by fire decreases evapotranspiration, leaving more water in the soil at the end of the growing season than would have occurred if vegetation had been undisturbed.

Prescribed burning.—Fire influences on soil water storage are expressed largely through their effects on evapotranspiration. A properly conducted prescribed burn normally does not greatly affect evapotranspiration and, consequently, little change in the soil water storage is expected.

Wildfire and slash burning.—Wildfire, however, can consume substantial amounts of vegetation, lowering evapotranspiration, and thereby can reduce loss of soil water on a watershed. Minimum soil water content in the fall is often increased compared with prefire conditions. Because of reduced soil water storage capacity, subsequent precipitation is more likely to generate runoff here than on an undisturbed area. A reversed situation has been observed, however, in a severely burned ponderosa pine watershed where increased soil water storage capacity was attributed to greater runoff conditions because of water repellency of the soil and to increased drying of the more exposed soil (Campbell et al. 1977).

Snow Accumulation and Melt

Total snow water equivalent on a watershed at any time throughout the winter is primarily a function of the total snowfall. Additional snow is often deposited directly into small openings in the forest canopy because of increased turbulence (Troendle 1983) or as a savings through the reduction in snow interception by the forest canopy (Baker, in press; Troendle and Meiman 1984, 1986). Important site variables affecting snow accumulation included elevation, aspect, vegetation type, size of trees, the canopy density, and size of openings in the forest canopy. In general, snow accumulation is found to be inversely proportional to vegetation density. Although prescribed fire would have limited effect on canopy interception, openings created by wildfire can influence snow accumulation.

No studies were found documenting the effects of fire on snowmelt rates. However, it is likely that scorching of surface litter and boles of trees would initially increase longwave reradiation to the snowpack, thereby accelerating snowmelt rates even more than those reported in openings created by logging.

Surface Erosion

Erosion in the arid Southwest must be viewed as an unsteady or discontinuous process which transports sediment from a source and through a channel system with intermittent periods of storage (Wolman 1977). This episodic transport process is more characteristic of arid or semiarid climate than of humid regions because the major cause of erosion in the Southwest is the "big" storm. These big storms move materials from various sources, including the material temporarily stored in the channel system. The disproportionate amount of sediment and debris moved during these major storms makes it difficult to define a "normal rate" of erosion either in the undisturbed or treated condition (DeBano 1977).

Large areas cleared by fires are vulnerable to erosion and can yield substantial amounts of eroded materials if subjected to large, high-intensity summer storms immediately after exposure. Erosion during the winter season is usually less.

Surface erosion, including sheet erosion and rilling, can be defined as the movement of individual soil particles by water or wind; it is a function of available forces, soil surface protection, and the inherent erodibility of the soil. Fire may influence the forces causing erosion by increasing effective precipitation, wind movement, and overland flow.

Fire-induced erosion is greatest in brush and grasslands under a Mediterranean-type climate (frequent droughts and low relative humidity) (Wells 1981). In the 400- to 500-mm annual rainfall region, low soil moisture and poor fertility may delay regrowth and increase erosion. Annual burning often reduces vegetative and litter cover to the point of accelerating erosion, while occasional burning or natural fires usually lead to less long-term erosion unless followed by abusive cultivation, overgrazing, or haphazard timber salvage.

Protection of the soil surface in Arizona chaparral is temporarily reduced by losses of vegetation and surface litter through burning (Pase and Lindenmuth 1971). Soil erodibility is also increased because of the volatilization of soil organic matter and destruction of soil aggregates. The net effect of burning is often an increase in surface erosion (Hibbert et al. 1974, Krammes 1960, Sinclair 1954). However, early establishment of a good grass cover following a fire, and subsequent conservative management, virtually assures soil stability and low sediment yields on moderate slopes (Pase and Granfelt 1977, Wright et al. 1982).

Values shown in table 1 are indications of variability of sediment delivery in response to fire in the Southwest. Documentation of the direct causes of these levels and the great differences among levels has been achieved in only a few studies. Although wildfire has an obvious effect on sedimentation, prescribed burning will generally result in much less sediment production (table 1).

Prescribed burning.—Prescribed burns, by design, do not completely consume extensive areas of organic matter. Therefore, the mosaic pattern produced by restricting the areal extent and degree of water repellency often reduces the amount of soil movement within and from the watershed.

The limited information available on erosion following prescribed burning in chaparral indicates slope, litter, and storm intensity are of major importance (DeBano and Conrad 1976, Pase and Lindenmuth 1971). Erosion increases with slope steepness, the percent of litter removed, and precipitation intensity. High enough intensities can eventually overshadow importance of slope and litter cover.

Studies on ponderosa pine sites in California and Arizona show similar effects of prescribed burning on erosion. In two study areas, a sufficient layer of organic material remained after burning to protect the soil from extensive erosion (Biswell and Schultz 1957, Cooper 1961). In an area in Arizona, erosion occurred only where less than 60% litter cover remained after burning (Pase and Lindenmuth 1971). Although significant increases in the frequency of soil exposure and movement can result after burning, most eroded material only moves a short distance downslope (Cooper 1961).

Wildfire and slash burning.—Intense fires can reduce surface resistance to erosional processes so that critical threshold conditions for soil mobilization and transport are more readily attained. Accelerated erosion appears to result primarily from partial or complete removal of the protective cover (forest floor), leaving the soil surface exposed to the unrestrained erosive forces of raindrop splash and overland flow. Raindrop impact on bare soil directly detaches and moves soil particles over short distances. By dispersing soil fines, splash also tends to seal the surface. This reduces infiltration and promotes overland flow, the process which transports eroded materials over longer distances.

In some areas, notably steep, brush-covered slopes of southern California, fire may increase erosion by loosening surface soil and rocks, causing shallow mass wasting; exposing bare soil to raindrop impact and rill erosion; rendering the top mineral soil layer temporarily nonwettable, thus causing overland flow during the first rain; and sealing the

Table 1.—Effects of fire on sediment delivery.

Author	Vegetation	Location	Treatment	Sediment transport	
				Control	Posttreatment
				$kg\ ha^{-1}yr^{-1}$	
Glendening et al. (1961)	Chaparral	Arizona	Wildfire	175	204,000
Wright et al. (1976)	Oak-juniper	Texas	Broadcast burn	0.02	28
Biswell and Schultz (1957)	Ponderosa pine	California	Understory burn	0	0
Krammes (1960)	Chaparral	California	Wildfire	5530	55,300
Campbell et al. (1977)	Ponderosa pine	Arizona	Wildfire	0-3	1-1254

surface pores of the soil by splash erosion.

Dry ravel from steep, unburned chaparral slopes can vary from 224 to 4300 kg/ha (Anderson et al. 1959). Dry ravel is accelerated during and immediately after fire, before the rainy season starts. Because dry ravel occurs in the absence of streamflow, debris routinely accumulates in deposits at the base of steep slopes. These deposits, along with untransported remnants of landslide debris, are readily transported downstream when high flood flows occur.

Reported erosion rates that occur in chaparral in the first year after a wildfire range from 9 to 35 times the normal rate, and rates 12 times normal can occur in the second year (Davis 1977, Hibbert 1985, Krammes 1960, Rowe et al. 1954). Largest sources of sediment in chaparral are from scour of residual sediment in the channel, then from rills and gullies, and finally, small quantities from wind, dry ravel, and landslides (Rice 1974). Most of sediment in the channel originates upslope, with landslides and dry ravel as primary contributors.

After the first postfire year, sediment yields usually reflect variation in rainfall and increasing stabilization of slopes and channel bottoms (Pase and Ingebo 1965). Sediment yield from grass-converted watersheds decreases faster than from watersheds that are allowed to recover naturally to chaparral. Slopes on the grass-converted watershed are fairly well stabilized in a matter of years (5 to 10 years) after a fire, and heavy grass cover along the more moist stream channels is often able to anchor much of the deposited sediments. Sediment yields generally drop to near preburn levels within 3 to 5 years (Pase and Ingebo 1965, Pase and Lindenmuth 1971).

Mass soil slippage is usually accelerated on chaparral areas after wildfires in southern California, where slopes are at or near the angle of repose and where rainfall is often heavy. While this type of erosion is not as common in Arizona chaparral, it cannot be excluded entirely as a potential hazard on steep, disturbed slopes (Hibbert et al. 1975).

Substantial erosion (up to 12 tons/ha) can occur after wildfires on conifer watersheds (Campbell et al. 1977, Rich 1962). These sediment yields usually drop to preburn levels in a matter of years.

DOWNSTREAM EFFECTS

The responses of streamflow to on-site effects can result in changes in total annual discharge, peak discharge, stormflows, baseflow, and timing of flow. Water quality and aquatic habitat may also be affected.

Flow Effects

Response to prescribed burning.—There is little information concerning downstream responses below prescribed burned areas. However, because responses below wildfire areas often last only a few years and sometimes only the first runoff season, we can assume that the detection of downstream effects caused by prescribed burning is going to be difficult, if not impossible, to detect. The study of downstream effects on riparian areas, below both wildfire and prescribed burned areas, is definitely needed.

Response to wildfire.—There is little doubt that wildfire can have an influence on downstream environments. As previously discussed, wildfire can have a major influence on vegetation and ground cover resulting in reduced infiltration and increased overland flow. Stormflow increases of threefold to fivefold during the first rainy season are typical in chaparral watershed following a wildfire (Davis 1977, Hibbert 1984, Rowe et al. 1954, Sinclair and Hamilton 1955).

Summer storms in typical, Arizona chaparral account for one-fourth of the annual precipitation, but contribute little to runoff (Hibbert 1984). Even stormflow from intense rain events is generally negligible. However, summer storms after a wildfire can produce a disproportionate amount of stormflow that drops off markedly in a short period of time, often after the first summer season.

In addition to increased stormflows, there is also evidence that wildfires increase baseflow or dry-season flow in chaparral (Colman 1953, Crouse 1961). In Arizona, intermittent streamflow prior to burning can become continuous (Pase and Ingebo 1965). Streamflow will eventually return to an intermittent condition, if the watershed is allowed to revegetate naturally to chaparral. However, if the watershed is converted to grass, perennial streamflow can be sustained.

Along with increases in stormflow and baseflow, there are also responses in peak discharges. Reported increases during the first postfire year in California and Arizona chaparral vary from 2 to 45 times normal, depending on storm size and antecedent moisture conditions (Glendening et al. 1961, Rowe et al. 1954, Sinclair and Hamilton 1955). The time required for peak discharge to return to normal depends on storm size, individual watershed characteristics, and the time needed for the vegetation to reestablish itself. Similar fire effects on peak discharges have been reported in ponderosa pine ecosystems in Arizona (Campbell et al. 1977, Rich 1962).

The hydrologic response to wildfire is documented, but how far downstream does the influence extend? Most of the flow in the Southwest comes during the spring. Therefore, any increases in streamflow because of fire are added to streams that are already flowing. It may be difficult to detect or measure these increases or subsequent losses in flow at any significant distance below a burned area.

Water Quality

Section 208 of the 1972 amendments to the Federal Water Pollution Control Act (Public Law 92-500) specifically mandates identification and control, to the extent possible, of nonpoint-source pollutions resulting from silvicultural activities (USDA Forest Service 1979). The National Forest Management Act (Public Law 94-588), also specifies that land management plans ensure protection of soil and watershed resources.

Sediment

Increased sediment is an important water quality response associated with fire. This subject has been addressed under the section "Surface Erosion."

Fire Influence on Nutrient Losses

Plant communities accumulate and cycle substantial quantities of nutrients in their role as the biological continuum linking soil, water, and atmosphere. Nutrients are cycled in an orderly and predictable manner unless some natural- or human-caused disturbance alters their form or distribution. During a fire, nutrients incorporated in vegetation, litter, and soil can potentially be volatilized during combustion, mineralized during oxidation, or lost by ash convection (Grier 1975). After a fire, nutrients in the ash can be redistributed by wind or leached by water. Part of the plant- and litter-incorporated nutrients (N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn) are volatilized during a fire and removed from the system. Metallic nutrient elements such as Ca, Mg, and K are converted to oxides and deposited as ash on the soil surface. These oxides are relatively insoluble until they react with CO_2 and H_2O of the atmosphere and are converted to bicarbonate salts. These salts are substantially more soluble and vulnerable to loss by surface runoff and leaching. Reductions in plant and litter cover also increase erosion susceptibility of nutrients. Severing the soil-plant cycling mechanisms reduces nutrient uptake opportunities and further increases the potential for nutrient loss by leaching.

Prescribed burning.—Nutrients in small live twigs or dead plant material of chaparral species are either released in a highly soluble form and deposited on the soil surface or are lost by volatilization during fire (DeBano and Conrad 1978). These highly soluble plant nutrients on the soil surface may be used for plant growth or are easily lost by erosion. Increased solubility of nutrients on burned chaparral areas can lead to a lack of a fertilizer response on burned areas (DeBano and Conrad 1976). Above-normal movement of nutrients to streams by surface erosion and leaching has the potential for impairing quality of surface water for municipal purposes, causing eutrophication of aquatic habitats, and lowering of site productivity.

Wildfire and slash burning.—In a study of the effects of fuelwood harvesting and slash burning on nutrient relationships in a pinyon-juniper stand, fuelwood in juniper trees (all material larger than 7.6 cm in diameter) made up about 38% of the tree biomass and contained 25% of the N, 13% of the P, 10% of the K, 25% of the Ca, 12% of the Mg, and 23% of the S in the aboveground tree components (DeBano et al. 1987). Although the leaves made up only 22% of the aboveground biomass, they contained higher percentages of the N, P, K, Mg, and S than the other plant parts. This nutrient distribution is important not only from the standpoint of nutrient removed as fuelwood but also because the nutrients in the slash are exposed to heating when the slash is burned. Slash burning acts as a rapid mineralizing agent for the nutrients contained in the slash, releasing significant quantities of total N, P, K, Ca, and Mg; depositing them on the soil surface.

Bicarbonate Response in Soil Solution and Streamflow

Bicarbonate ions in soil solution and in streamflow are increased as a consequence of burning. The bicarbonate ion is the principal anion in soil solution, is an end product of root respiration in an undisturbed forest, and is a product of oxide conversion following fire. Concomitant fluctuations of bicarbonate and cation concentrations indicate that bicarbonate is the main carrier of cations in the soil solution (Davis 1987).

Nitrogen Response in Soil Solution and Streamflow

Nitrate-N (NO_3), ammonium-N (NH_4-N), and organic-N are the nitrogen forms most commonly studied as indicators of effects of disturbance or land management activity on water quality. Nitrate-N is one of the most mobile ions in soil-water systems and is one of two forms of N used by plants. Maximum recommended levels of NO_3-N in streamflow is 10 mg/L (EPA 1973).

Prescribed burning.—Prescribed burning in California chaparral results in losses of N by volatilization and erosion (DeBano and Conrad 1978). Although this loss represents only 11% (161 kg/ha) of the N in the plants, litter, and upper 10 cm of soil, frequently burned sites would soon be devoid of N if this amount were lost during each fire without a mechanism for replenishing it. We know that precipitation contains some N, although this input amount is probably minimal. A more important input mechanism seems to be nitrogen-fixing organisms. Some shrubs develop root nodules capable of fixing up to 60 kg/ha of N annually under optimum conditions and other postfire leguminous herbs undoubtedly also fix N (DeBano and Conrad 1978). Nitrogen fixation by nonsymbiotic organisms may also replenish N after a fire, although this source has received little study.

Wildfire and slash burning.—Nitrogen concentrations are normally very low (less than 1 mg/L) in Southwest streams draining undisturbed areas (Davis 1984). Maximum levels of NO_3-N concentration in response to wildfire, alone, range from 0.01 mg/L (Johnson and Needham 1966) to 2.0 mg/L (Longstreth and Patten 1975) (table 2).

Nitrate-N increases in streams appear to be a result of acceleration of the nitrification process in the soil in response to more favorable pH and increased content of electrolytes (mainly Ca) (USDA Forest Service 1979). Nitrate-N easily moves with water through the soil profile to streams. The large increase of 56 mg/L observed in Arizona (table 2) is believed to be in response to NO_3-N release from the massive chaparral root system killed by the herbicide (Hibbert et al. 1974).

Ammonium-N concentration in streamflow can increase an order of magnitude (0.03-0.1 mg/L) after wildfire and concentrations of organic-N about double (Hoffman and Ferreira 1976). Displacement of organic detritus from the stream area because of increased flow and increased stream source area are probably the primary reason for the increased levels of organic-N (Tiedemann et al. 1978).

Phosphorus Response in Soil Solution and Streamflow

Phosphorus in soil solution, streamflow, and lakes is present mainly in two forms—the inorganic ortho-phosphate and organic phosphate as measured by the difference between total phosphate-P and ortho-phosphate-P. In most studies, total phosphate-P is reported as total P (T-P). Even though phosphate-P is an anion, it is not as readily leached as NO_3-N because it complexes readily with organic compounds in the soil (Black 1968).

Phosphorus compounds in pinyon-juniper woodlands are distributed in a mosaic pattern reflecting differences in litter and duff distribution between individual tree species and between tree canopies and interspaces (DeBano and Klopatek 1988). Juniper litter and duff contains higher concentrations of total P and bicarbonate-extractable P than pinyon litter and duff.

Prescribed burning.—Only about 5% (32.1 kg/ha) of the P in California chaparral is contained in the plants and litter (DeBano and Conrad 1978). Almost all P in the plants is returned to the soil surface as ash during prescribed burning because it is concentrated in the smaller plant stems that are easily consumed by the fire. Some P is usually lost by erosion after a burn.

Wildfire and slash burning.—Burning has significant direct and indirect effects on the P cycling process. DeBano and Klopatek (1988) suggest that not only are large amounts of P lost from pinyon-juniper litter during slash burning, but smaller, significant increases in available soil P also occur. About 50% of the total P contained in the litter is lost during combustion. The remaining P in the ash is also susceptible to wind and water erosion, as well as fixation by carbonates.

Phosphorus concentrations have been found to increase in overland flow from slash burning and wildfire areas; but these increases are not usually sufficient to alter quality of stream or lake water (Gifford et al. 1976, Longstreth and Patten 1975).

Cation Response in Soil Solution and Streamflow

Fire substantially alters the form and distribution of cations, making them vulnerable to removal by runoff and leaching. Responses of cations to burning are difficult to interpret because of different amounts in plant biomass and litter, different fire intensities, different exchange capacities of humus and soil, and different moisture fluxes and timing. Studies of soil solutions and surface runoff following fire indicate increases in levels of cations such as Ca, Mg, K, Na, and Mn (Gifford et al. 1976, Sims et al. 1981).

Prescribed burning.—Potassium seems to have a special role in nutrient recycling during fire because a large proportion of this element is contained in the plants and litter. About 73%, or 287 kg/ha, of the K in chaparral is found in the plants and litter (DeBano and Conrad 1978). During prescribed burning, about 15% (44 kg/ha) of the K in the plants is deposited as ash on the soil surface and another 15% is lost—possibly by volatilization. An additional 10% is also lost by erosion and runoff after the fire.

Although 45 kg/ha of Ca, 14.4 kg/ha of Mg, and 5.3 kg/ha of Na are

Table 2.—Effects of fire and selected treatments on maximum NO3-N concentration in streamflow.

Author	Vegetation	Location	Treatment	Maximum NO_3-N Control	Maximum NO_3-N Posttreatment
Hibbert et al. (1974)	Chaparral	Arizona	Herbicide, fire	0.20	56.00
Johnson and Needham (1966)	White-fir Ponderosa pine	California	Wildfire	0.01	0.01
Hoffman and Ferreira (1976)	Mixed conifer shrub	Sierra Nevada	Wildfire	0.06	0.30
Longstreth and Patten (1975)	Chaparral	Arizona	Wildfire, maintained in grass	0.10	2.00

translocated to the soil surface during prescribed burning in chaparral, their importance in nutrient cycling in this ecosystem is not fully known (DeBano and Conrad 1978). About 67 kg/ha of Ca, 32 kg/ha Mg, and 4.6 kg/ha of Na are also lost by erosion and runoff. This condition suggests that not only are soluble cations deposited in ash lost following burning but that some of these elements in the burned and unburned litter can also be eroded away.

Wildfire and slash burning.—Watershed studies provide an integrated view of the effects of fire on cation concentrations and losses. Johnson and Needham (1966) conducted the first watershed study of effects of fire on chemical water quality. They found no pronounced effect of wildfire on ionic composition and concluded that increased runoff resulting from cover reductions masked concentration effects. Longstreth and Patten (1975), however, found that Ca and K concentrations can increase after burning in chaparral.

Sediment Losses of Nutrients

Sediment losses of N, P, and cations in California chaparral can substantially exceed those lost in solution after a wildfire (DeBano and Conrad 1976). Nitrogen and P losses of 15.1 and 3.4 kg/ha, respectively, are reported in sediments as compared with only trace amounts found in solution. Loss of Ca, Mg, Na, and K in solution is about one-fourth of the loss on sediment. Overall, however, sediment and solution losses of nutrients often comprise only a minor proportion (0.7-8%) of the total prefire nutrient capital of plants, litter, and upper 10 cm of soil for N, P, K, Mg, Ca, and Na.

Aquatic Habitat Responses

Although there is an accumulating data base of effects of fire on nutrients and stream water chemistry, attendant responses at the stream level have not been well studied. Hoffman and Ferreira (1976) examined periphytic algae above and below burned sites in California and found essentially no difference in the similarity index, indicating that water quality changes did not exert any measurable effect on algae growth.

MANAGEMENT IMPLICATIONS

Fire can be used economically in managing and manipulating vegetation, often in an ecologically sound manner. Mechanical means of preparing seedbeds are expensive, and spraying with herbicides is not only expensive but also controversial. Initially, however, fire may need to be used in combination with other improvement methods.

Costs of fire suppression are increasing every year. Risk of wildfire can be reduced by the use of prescribed burning. A study of 26,000 ha of prescribed burn in Arizona showed that 82% fewer fires occurred in this area in the 3 years following control burning (Hedden 1957). Prescribed burning in some forest situations will result in some pruning of the lower tree branches and some reduction of stems and fuelwood. These factors often contribute to increases in environmental esthetics, better accessibility for recreational uses, increases in nutrient availability for plant growth, improved wildlife habitat, and a reduction in insect and disease damage.

Most land managers in the Southwest have responsibility for at least two or three vegetation types, and the influence of burning in these different ecosystems are usually different. Considerable information is available concerning hydrologic response to burning, particularly following wildfire. Generally, hydrologic responses after burning change proportionally with precipitation and are minor where annual precipitation is less than 460 mm (Hibbert 1979). This precipitation criterion applies to all desertscrub types, the semidesert grasslands, and much of the conifer woodland type (fig. 2). Therefore, only the montane conifer, much of the interior chaparral, and some of the conifer woodland type with annual precipitation regimes above 460 mm have the potential of exhibiting much of a hydrologic response to burning.

Because of the natural variability found in forest and range environments in the Southwest and in burning situations, fire influences are viewed as a continuum, with effects of prescribed burning at one extreme and wildfire at the other. Each burning situation, whether a prescribed burn or wildfire, will result in a mosaic pattern of site conditions. Land managers, consequently, must often deal with a wide spectrum of fire influence on a given burned area. However, with increased knowledge and its implementation, perhaps someday more time and money can be expended on the prescribed burning end of the scale.

Light, prescribed burns usually have minimal hydrologic impact on watersheds as the result of partial burning of the surface vegetation and litter and of the forest floor. Wildfire, however, can kill trees and other vegetation and can consume the forest floor over large areas of a watershed. As a result, wildfire can exert a pronounced effect on basic hydrologic processes, leading to increased sensitivity of the site to eroding forces and to reduced land stability. Response to fire is often exhibited as an increase in overland flow and an increase in peak and total stream discharge. These factors, consequently, provide the transport forces for removing sediment and nutrients from the site.

Erosion, in response to burning, is a function of several factors including degree of protective cover loss; steepness of slopes; degree of soil nonwettability; climatic characteristics; and rapidity of vegetation recovery. Resulting sedimentation and increased turbidity appear to be the most serious threats to water resources following fire.

Most of the streamflow in the Southwest comes during the spring runoff period. Therefore, any increases due to burning will normally be added to flowing streams. Consequently, it may be difficult to detect or measure any effect of fire even below severely burned areas. Most evidence suggests that even after wildfires, responses in streamflow and sediment yields drop to near preburn levels within 3 to 5 years.

The influence of burning on nutrients is not as clear. Fire causes rapid mineralization and mobilization of nutrient elements that are manifested as increased levels of nutrients in overland flow and in soil solution. Burning can also result in the loss of various amounts of some elements by volitalization and convection. Studies indicate that additional nutrients in streamflow after burning do not significantly impair the quality of surface waters for municipal purposes, but more information is needed on this subject and on their effects on the riparian community.

Often nutrient losses following fire are not large compared with the total amount of nutrients on the site. However, what effect the periodic losses of nutrients have on "watershed condition" or what "cumulative effects" these losses have on site productivity are not well established.

Prescribed burning can be used as a management tool in the various vegetation types found in the Southwest. However, land managers must always be aware of the delicate balance that exists within the soil-plant-water-atmosphere system and how easily it can be, either positively or negatively, influenced by fire. Two major gaps in our knowledge are the cumulative effects of burning on watershed condition, and the effects of burning on riparian habitat. These two areas must be studied before the full potential of prescribed burning can be realized.

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