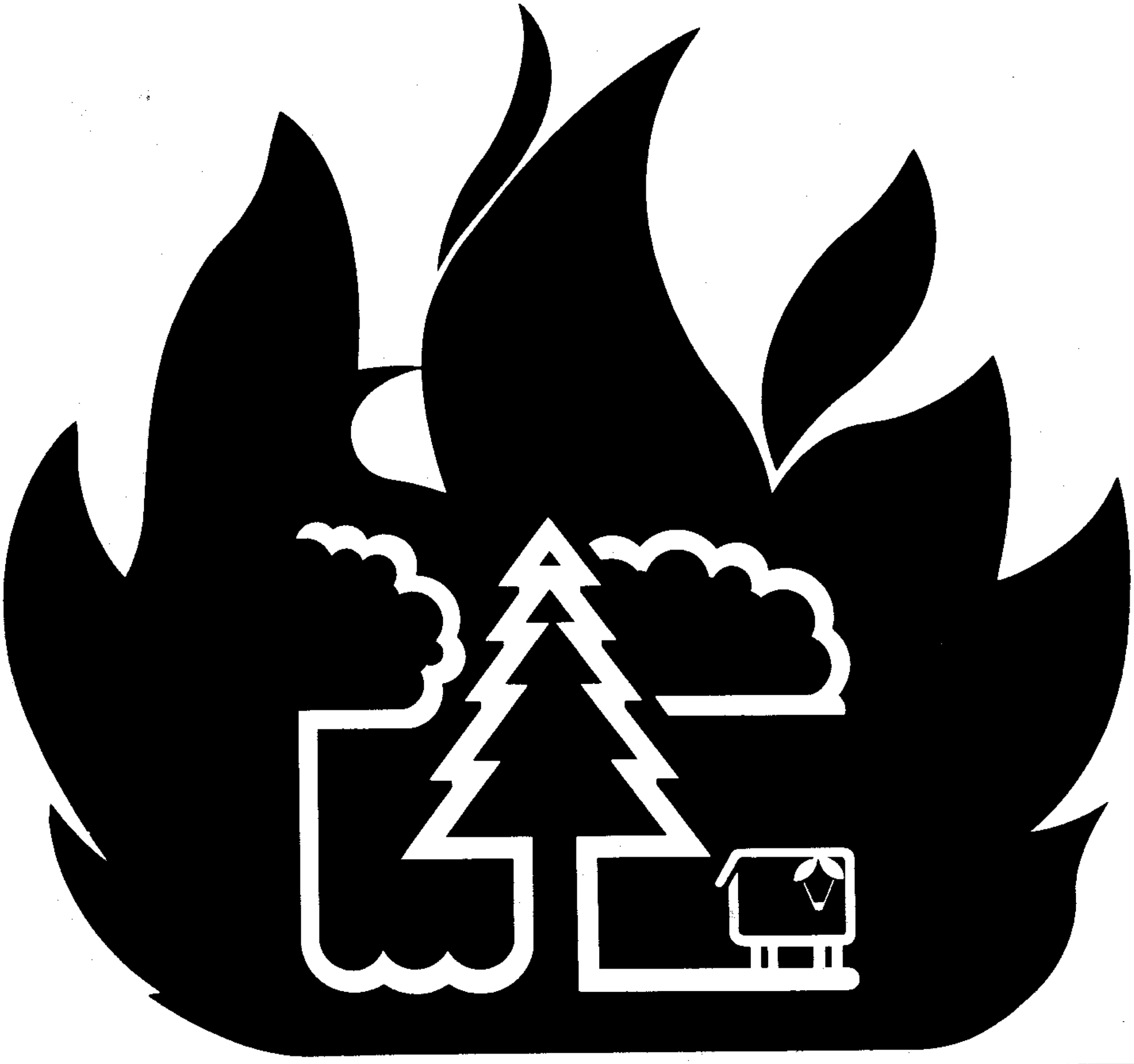
Effects of Fire on Water

A State-of-Knowledge Review
National Fire Effects Workshop
Denver, Colorado
April 10-14, 1978



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EFFECTS
OF
FIRE ON WATER

A State-of-Knowledge Review

Prepared for the Forest Service
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Denver, Colo., April 10-14, 1978

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PREFACE

Recent changes in Forest Service fire management policy make it clear that resource managers today need a great deal more information on the physical, biological, and ecological effects of fire. They will need information on fire behavior and fire effects as a basis for analyzing the benefits, damages, and values of various fire management alternatives. Managers must be able to place a value on all resources if they are going to incorporate fire and its effects into land management plans. The Forest Service is committed to the concept that fire management planning has to be a fundamental part of all our planning.

Recent laws and regulations also give additional guidance for the Forest Service to use in developing land management plans for each unit of the National Forest System. These plans must coordinate outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness resources. Interdisciplinary planning is vital, and research must cover the same universe as our planning; therefore, interdisciplinary research is a must.

The effects of fire have been studied since the beginning of organized Forest Service research, but the results are scattered over a wide range of outlets. In addition, research is conducted on the effects of fire under several appropriation line items, and in some instances lacks the interdisciplinary approach needed to make the results as useful as possible to land managers.

The National Fire Effects Workshop was held April 10 through 14, 1978, as a first step in responding to the most recent changes in policies, laws, regulations, and initiatives. One of the major Workshop objectives was to prepare a report indicating the current state-of-knowledge about the effects of fire on various resources. These reports formed the basis for pinpointing knowledge gaps. Using this information and input from land managers, priorities for research needed on the effects of fire were established.

Six work groups were established to prepare the state-of-knowledge reports on the following subjects: soil, water, air, flora, fauna, and fuels. Work group members were mainly Forest Service research scientists, but other individuals from the Forest Service, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Bureau of Indian Affairs also participated.

We hope these state-of-knowledge reports will prove useful to researchers and research planners, as well as to land and fire management planners. Each report will be published as an individual document. A separate bibliography will also be included in this series in an effort to provide a source document for most of the literature dealing with the effects of fire.

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INTRODUCTION

Of all the ecosystem components, water is perhaps the most sensitive to the disturbance of vegetation and soils on the land surface. Water is not only a valuable resource product from forests and rangelands, but is also the principal carrier of nutrients through the soil-plant-water-atmospheric continuum. Water responds to disturbances through a variety of characteristics including: timing and quantity of flow, physical parameters, such as temperature, sediment content, dissolved oxygen; and biological and chemical constituents and characteristics.

Effects of various land treatment measures and disturbances have been best characterized for water quantity and timing. Interest in water as a response indicator of forest cover alterations dates to the early 1900's; timing, peak discharge, water yield, and sediment were the principal hydrologic responses of interest in research programs aimed at improving water yields from forests and rangelands.

In the 1960's, the emphasis shifted markedly to utilization of chemical, physical, and biological water quality parameters as indicators of nonpoint sources of pollution resulting from silviculture activities. Since prescribed burning is probably the most widely used treatment in management of forests and rangelands and is an important part of the Forest Service's new fire management policy, it is appropriate and timely to assemble our current knowledge of effects of fire on water.

Research on effects of fire on water interfaces closely with and probably overlaps some of the research discussed in the Effects of Fire on Soils, A State-of-Knowledge Review GTR WO-7. Nonetheless, an understanding of the cycling processes on the land surface is basic to an understanding of the hydrologic responses to disturbance observed at the stream and lake level.

In this review, studies of wildfire and prescribed burning have been utilized for an assessment of fire effects. However, in areas typified by low acreage burned (Northeast United States, for example), little information is available. For such areas we have utilized information from studies not involving fire to obtain estimates of responses that may be anticipated from burning. We felt this was necessary because of widening interest in these regions for the use of fire for silvicultural purposes and for wildlife habitat improvement.

Where possible, we have included information on effects of wildfire suppression activities, such as mechanical fireline construction and aerial application of retardant chemicals. Discussion of fireline construction activities is especially pertinent for Alaskan permafrost situations. The scope of this review has been expanded to include effects of post-wildfire and post-prescribed burn activities, such as erosion control fertilization, since these are integral parts of fire management programs.

Field studies to determine the effects of fire on water resources have generally used three principal approaches:

Unit watershed or catchment study.—This involves establishment of the relationship among several watersheds for precipitation input, stream discharge, timing, temperature, and water quality during a calibration or pretreatment period. Responses to treatment on one or more watersheds for these parameters are compared to the pretreatment period and one or more untreated control watersheds.

Lysimetric or runoff plot study.—This study uses an approach similar to the unit watershed or catchment study but on a small plot scale. An area is physically delineated where precipitation input can be determined for a unit area or applied artificially. Discharge can be collected and measured or depth and duration of flow can be measured. Changes in quantity and quality of water following treatment of this known area of land can be readily determined.

Tension lysimetry study.—In this approach moisture is pulled from the soil through porous cups or plates under tension.

A discussion of the advantages and disadvantages of the various approaches is beyond the scope of this review; refer to Hewlett (1970) and Hewlett et al. (1969) for discussions of the merits of various approaches for studying water responses to management practices and other perturbations.

FIRE AND HYDROLOGIC PROCESSES: ONSITE EFFECTS

Hydrologic processes that may be affected by fire include: interception, infiltration, soil moisture storage, snow accumulation, snowmelt, overland flow, surface erosion, and mass erosion.

RAINFALL INTERCEPTION

Interception is the process whereby vegetation interrupts the fall of precipitation onto the soil surface. For this discussion, the forest floor (including vegetation, litter, and decomposed organic matter above the mineral soil) is also considered an interception body. Perhaps the most important function of the interception process is reduction of raindrop impact at the soil surface. This detachment coupled with overland flow is an important component of the erosion process (Farmer 1973). Hewlett and Nutter (1969) estimated that the kinetic energy of 2.5 centimeters of rain on 929 square centimeters of bare soil is 68 joules (50.4 foot/pounds). Osborn (1954a) showed that 5 centimeters of rainfall might detach and set in motion 179 metric tons of soil material per hectare. The effectiveness of vegetative cover in preventing soil erosion splash is directly proportional to the amount of cover (Osborn 1954b).

Originally, precipitation retained or detained on the vegetation and evaporated was referred to as interception loss. However, Rutter (1967) stated that on the average, interception reduces transpiration losses by about 20 percent. The amount of water required to wet the vegetation (average rainfall storage value) ranges from 0.03 to 0.23 centimeters for coniferous and hardwood forests of the United States, according to a review by Helvey (1971). A summary by Zinke (1967) showed that interception by shrubs and grasses averages 0.13 centimeters. Forest floor interception storage ranges from 2 to 27 percent of the gross precipitation (Helvey 1971). Zinke (1967) reported that storage values for the forest floor average about 0.41 centimeters, but other studies indicate the average may be closer to 0.30 centimeters (Kittredge 1955, Garcia and Pase 1967, Clary and Ffolliott 1969).

Interception losses during individual rainstorms are a function of the interception storage and of meteorological conditions 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 percent.

Removal of vegetation and the underlying forest floor by fire decreases the amount of interception thereby increasing the potential for runoff. No studies were found that provide direct measures of change in interception loss by fire. It is likely that almost all interception is temporarily eliminated by an intense burn, whereas a light understory burn may have little or no effect. Muol and Buell (1955) demonstrated the importance of mosses in the interception process in New Jersey pine barrens. Moss cover that develops following forest fire may absorb an average of 1.3 to 1.7 centimeters of precipitation. However, these authors pointed out that the moss layer is not as effective for soil protection as the thick litter layer that develops in unburned areas.

INFILTRATION

Infiltration may be defined as the amount of water that can be absorbed by soil in a given time period. If more water is supplied than can infiltrate, the excess is available for rapid runoff as overland flow. Sprinkling infiltrometers have been used in numerous infiltration studies on forest lands. Some important variables found to affect infiltration under simulated high-intensity rainfall rates (9.1 to 12.7 centimeters per hour) include: percentage ground cover, vegetative cover type, soil volume-weight, weight of the dead organic material, and other protective cover (Dortignac and Love 1961, Meeuwig 1965, Bethlahmy 1967). Many of these factors may be adversely affected by fire and result in reduced infiltration and increased overland flow.

DeByle and Packer (1972) reported that logging reduced soil bulk density and increased porosity but subsequent prescribed fire exerted an opposite effect. Arend (1941) demonstrated a significant reduction of infiltration rate of 2.03 centimeters per hour on plots burned annually for 6 years compared to unburned plots in the Missouri Ozarks. Burning caused approximately a three-fold reduction in infiltration in oak woodland on silt loam soils in Illinois (Auten 1934).

Fire also influences microclimate on a site in a variety of ways including greater temperature extremes for both air and soil (Fowler and Helvey 1978). Such changes increase the potential for soil frost formation which, if of the concrete type, can cause a dramatic reduction in infiltration (Bullard 1954).

In chaparral zones of southern California, fire has been shown to create water repellent layers in the soil (Krammes and DeBano 1965, DeBano and Krammes 1966, DeBano et al. 1970). These layers create a nonwettable condition that seriously inhibits infiltration and are a major cause of increased overland flow (DeBano 1971, Rice 1974). Nonwettability increases as intensity of fire increases. Although water repellency problems are most pronounced in chaparral zones, the problem is not confined to southern California. Dyrness (1976) demonstrated increased water repellency in the upper 23 centimeters of soil for 5 years following wildfire in lodgepole pine stands of the upper Cascade slopes in Oregon. Following wildfire in a ponderosa pine habitat, Campbell et al. (1977) found that soils of sandy texture developed water repellency that persisted for 4 years. Infiltration was reduced from 6.8 centimeters per hour on an unburned area to 2.6 centimeters per hour on areas that were severely burned.

SOIL MOISTURE STORAGE

Throughout most of the United States, the soil mantle is recharged to capacity or to near capacity during the springtime. At the start of the growing season, transpiration proceeds rapidly from the readily available moisture stored in the soil. As the season progresses, the water stored in the soil is diminished. The water deficit that usually exists in the soil by the fall is subsequently reduced through the winter and early spring. Vegetation removal by fire can leave considerably more water in the soil at the end of the growing season than would have existed if the vegetation had been undisturbed, because of a net decrease in evapotranspiration.

Following a wildfire in north-central Washington, Klock and Helvey (1976b) observed an 11.6 centimeter increase in minimum autumnal moisture in the upper 120 centimeters of soil compared to the prefire conditions. Because of the reduced moisture storage capacity of the soil mantle, subsequent precipitation was thus more likely to generate runoff here than on an undisturbed area. Klock and Helvey (1976a) emphasized that higher autumnal soil moisture following fire was an important factor in mass soil movement on steep mountain slopes.

Trends in autumnal soil moisture for 3 years after fire, observed by Klock and Helvey (1976b) indicated that soil moisture might return to prefire levels about 5 years after fire. However, they did not anticipate such a quick return because vegetation composition would not be the same as it was prior to fire. Also, minimum autumnal soil moisture in nearby clearcut areas 10 years after harvest was still greater than prior to harvest (Herring 1968).

In contrast to results showing increased soil moisture after vegetation removal, Campbell et al. (1977) observed reduced soil moisture in the upper 30 centimeters in an area severely burned by wildfire compared to an undisturbed area. They attributed the difference to greater runoff from the burned area. Summer drying of this soil layer was also more pronounced in burned than unburned areas.

Studies of soil moisture storage directed at the effects of logging rather than fire support the results of Klock and Helvey (1976b). Ziemer (1964) studied soil moisture depletion in the subalpine forest zone on the western slope of the Sierra Nevada mountains. Soil moisture in 122 centimeters of soil was increased 17.5, 7.4, 3.0, and 1.8 centimeters in logged areas of cuttings of 1, 5, 10, and 12 years of age, respectively. Croft and Monninger (1953) found that soil moisture at the end of the growing season increased 10.2 centimeters following removal of aspen trees and 20.4 centimeters when both aspen and understory herbaceous cover were removed.

SNOW ACCUMULATION

The total snow water equivalent on a watershed at any time throughout the winter is primarily a function of the total snowfall. Other factors of importance include evaporation losses or gains (including interception), snowmelt during the accumulation season, and the effects of wind on the pattern of snow accumulation and its subsequent redistribution. All these factors may be affected by vegetation to some degree and consequently by fire.

Meiman (1968) presented a comprehensive summary of most of the North American studies to date. Important site variables identified as affecting snow accumulation included: elevation, aspect, vegetation type, size of trees, the canopy density, and size of openings in the trees. In general, snow accumulation was found to be inversely proportional to the amount of vegetative cover. Six different studies reported that removal of western tree species by various cutting methods (selection, strip, and patch cutting) resulted in increased snow accumulation, ranging from about 10 to 50 percent and averaging 25 percent. The higher values tended to result from patch and strip cutting rather than selection cutting.

Although no studies were found that evaluated the direct effects of fire on snow accumulation, the studies reported above suggest that greater accumulation will occur in small, hot burns, or in larger burns where some residual forest stand remains than in large, hot burns (e.g. greater than 4 hectares) where snow accumulation is reduced because of increased wind scour.

SNOWMELT

Several investigators have shown that spring snowmelt is more rapid in large natural forest openings or artificial openings created by clearcutting than in areas under the forest canopy (Haupt 1951, Berndt 1961 and 1965, Rothacher 1965, Gary and Coltharp 1967). Anderson (1956) attributed differences in snowmelt between openings of undisturbed areas in a red fir forest in California to shading by trees south of the openings and back radiation from trees on the north side of openings. In Anderson's study, melt rates under a dense forest cover averaged about 50 percent of those in a large opening.

The U.S. Army Corps of Engineers (1956) conducted comprehensive studies of the energy budget of the snowpack under open and forested conditions and concluded that melt rates are in general considerably greater in small clearings. No studies were found documenting the effects of fire on snowmelt rates. However, it is likely that scorching of ground materials and boles of trees would increase longwave radiation to the snowpack, thereby accelerating snowmelt rates even greater than those reported for logging.

OVERLAND FLOW

Overland flow occurs when the infiltration rate or capacity of a soil has been exceeded by the amount of incoming precipitation or by the rate of snowmelt. Independent variables include all the soil and plant factors that influence infiltration rate, intensity and duration of precipitation, steepness of slope, and whether or not the soil is frozen (Wisler and Brater 1959).

For unburned chaparral watersheds, Rice (1974) observed that overland flow rarely exceeds 1 percent of rainfall and is often nonexistent. In the first year after fire, he measured up to 40 percent of rainfall occurring as overland flow with the average ranging from 10 to 15 percent. In western Montana, DeByle and Packer (1972) observed that overland flow from snowmelt was up to eight times greater from logged and burned plots than from unburned. Treatments had reduced soil protective cover from 98 percent to less than 50 percent. Overland flow from snowmelt was greater than that resulting from summer storms. Summer storm overland flow was highly correlated with total summer precipitation. Reductions in summer storm overland flow observed in the third and fourth years after treatment were attributed to reduced precipitation and improved protective cover of vegetation.

Overland flow after prescribed burning on six miniwatersheds in dozed juniper lands of central Texas was directly related to slope steepness (Wright et al. 1976). On level watersheds (1 to 4 percent slope), overland flow was not affected by fire. On moderately steep slopes (8 to 20 percent slope), overland flow was greater than paired controls for the first 12 to 18 months. Overland flow on steep slopes (37 to 61 percent) was still greater than paired controls after 30 months and appeared to be related to the rate at which bare areas revegetate. Vegetation did not develop as rapidly or uniformly on steep slopes, as on moderately steep slopes.

In northern Mississippi, Ursic (1969 and 1970) found that prescribed burning on steep slopes caused increased overland flow. The most significant changes occurred on loess soils—the least on sandy soils. Ursic found that small changes in vegetation cover could greatly influence hydrologic responses of small headwater catchments. Stormflow responses were related to the presence or absence of a fragipan.

SURFACE EROSION

Surface erosion, including sheet erosion and rilling, can be defined as the movement of individual soil particles by water or wind, and is a function of forces available, protection afforded the soil surface, and the inherent erodibility of the soil. As described above, fire increases available forces by increasing effective precipitation, wind movement, and overland flow. Protection at the soil surface is reduced by losses of surface litter. Soil erodibility is increased because of the volatilization of soil organic matter and destruction of soil aggregates. As might be expected, the net effect of burning is toward increased surface erosion.

In western Montana, DeByle and Packer (1972) observed that soil erosion associated with overland flow from snowmelt increased from zero for control plots to 50 and 150 kilograms per hectare the first and second years, respectively, following logging and prescribed burning. Except for erosion of 1340 kilograms per hectare during a high intensity storm the first year after burning, erosion associated with summer storms was slightly less than that from snowmelt. However, because of splash erosion from raindrop impact, summer storms were a much more efficient eroding force than snowmelt runoff. Overland flow was less than a third of that during snowmelt and yet erosion rates were only slightly less. This is confirmed by comparing kinetic energy of raindrop action (68 joules) with that for overland flow (0.03 joules) on 929 square centimeters of bare soil (Hewlett and Nutter 1969).

Cooper (1961) found significant increases in erosion following controlled burning of ponderosa pine on basalt soils in Arizona. Sheet erosion and rilling on granitic soils in Idaho were both greatly accelerated following a wildfire on a clearcut area of mixed Douglas-fir-ponderosa pine (Megahan and Molitor 1975). An adjacent uncut area showed slight sheet erosion and no gullying following the fire. Connaughton (1935) evaluated effects of fire on erosion of granitic slopes in Idaho in relation to burn intensity, slope gradient, and logging. Erosion increased with both slope gradient and burn intensity and was higher on logged areas than on nonlogged areas.

Rowe et al. (1954) reported that erosion rates 35 times greater than normal could occur in the first year after a fire, and rates of 12 times normal could occur in the second year. Erosion rates observed by Davis (1977) for nine large watersheds in the San Gabriel Mountains essentially agreed with those of

Rowe et al. It is generally accepted that watershed erosion rates do not return to normal until 10 years following a fire.

Runoff and erosion in the taiga of Alaska appear to be less responsive to fire than other areas of the United States. According to Viereck (1973a), this results from the high water holding capacity of the organic layers, rapid revegetation of partially burned organic soils, long periods when the soil is frozen, and low intensity of summer rainfall. However, construction of firelines on permafrost is one of the most protracted and serious consequences of forest fires. Long-lasting impacts are greatest along small watercourses in valley bottoms where the substrate consists of organic soils underlain by permafrost (Lotspeich et al. 1970, DeLeonardis 1971, Viereck 1973b). When the vegetation and organic mat are removed, the permafrost melts, releasing large quantities of water and initiating a series of water-filled depressions. This problem is compounded if a nearby stream is captured by the system so that more water is available for melting the permafrost and for eroding the surrounding silt.

The combination of melting ice wedges and water erosion may result in erosion ditches 5 to 10 meters deep even on relatively gentle terrain. Revegetation of these ditches is slow because of the continuous slumping and erosion—5 to 10 years after a fire there may still be active erosion even though the surrounding burned area has nearly recovered from the effects of the burn. Considerable effort is now made in Alaska to locate firelines away from low-lying permafrost sites, and quick rehabilitation of firelines is done whenever possible by construction of water bars, seeding, and fertilization (Bolstad 1971).

Also in contrast to erosion observed following fire in much of the United States, initial and repeat prescribed burning during various seasons did not affect such movement in the Georgia Piedmont (Brender and Cooper 1968). Even 18 cm of rain in August with heavy downpours failed to initiate erosion. Similarly, Cushwa et al. (1971) failed to detect soil movement in established gullies after prescribed burning in the South Carolina Piedmont. Most studies in the Southeastern Coastal Plain conclude that periodic fire (wild or prescribed) has little impact on soil physical properties that affect infiltration rates or erosion (Suman and Halls 1955, Metz et al. 1961, Moehring et al. 1966, Ralston and Hatchel 1971, Stone 1971, and Pritchett 1977). Large pore space may decrease and percolation may slow with short interval (1 to 2 years) burns, but erosional consequences are negligible.

MASS EROSION

Mass erosion, the downslope movement of a portion of the landscape under direct application of gravitational forces, has been documented as an important postfire erosional phenomenon in southern California, the Pacific Northwest, and the Intermountain West (Croft and Adams 1950, Sinclair and Hamilton 1955, Jensen and Cole 1965, Swanston 1971, Rice 1974, and Klock and Helvey 1976a). This type of erosion has caused loss of life, destruction of roads and buildings, loss of aquatic habitats, and inundation of agricultural areas. For example, debris flows in north central Washington, following wildfire, killed four people and destroyed several residences (Klock and Helvey 1976a). Several thousand cubic meters of debris were estimated to have flowed from one watershed. Jensen and Cole (1965) reported that an intense fire on 364 hectares of steep slopes adjacent to the south fork of the Salmon River in Idaho caused mass landslide erosion that delivered 34,400 cubic meters of debris directly to the river.

Causative mechanisms and processes of mass erosion are complex and generally not well studied. However, the principal elements responsible for mass erosion in most areas are elimination of stability provided by roots of vegetation and high soil pore water pressures resulting from removal of transpiration draft (Swanston 1971, Klock 1978). Mass movement either develops or is accelerated during periods of abnormally high rainfall and is closely related to peakflows generated by such storms (Swanston 1971).

In addition, soil nonwettability has been identified as an important contributing factor in debris flows or floods in California (Rice 1974, DeBano et al. 1977). Whereas the formation of nonwettable soils has been studied in detail, the gross effect on the hydrologic processes of watersheds has not. It is known, for example, that the nonwettable layer is not continuous over a burned watershed. However, its relative continuity and the hydrologic effect associated with this continuity is not known. It is assumed that this continuity is associated with intensity of burn, but we have not yet learned how to characterize this association so that it can be applied in the field.

Rice (1974) measured landslide volumes from chaparral watersheds that were recently burned (1 year), unburned for 9 years, and unburned for 50 years. Landslide volumes from the watershed that was unburned for 9 years exceeded those from the recently burned watershed by nearly 30 times. He concluded that the recently burned watershed was spared erosion because water repellent layers prevented infiltration and the roots of shrubs were still intact. Despite heavy vegetative cover, the watershed that was unburned for 50 years exhibited greater landslide volume (1.6 times) than the recently burned watershed. Rice attributed this to high infiltration rates on this watershed.

Mass erosion events in California chaparral are most commonly manifested as debris floods or debris flows. The debris bulking ratio (ratio of volume of debris to volume of water) increases from 2 to 15 times following fire (Rowe et al. 1954, Sinclair and Hamilton 1955). Increased debris bulking ratio coupled with increased storm runoff is the principal cause of disastrous debris floods that occur in southern California.

Klock and Helvey (1976a) attributed an early spring debris flow from a burned watershed to accelerated melting of a record high snowpack by unseasonably warm weather. The result was a midslope "blowout" of a small pocket of soil violently displaced by high pore water pressures. Material from the blowout plugged the main channel of the watershed that moved "en masse" to the valley floor after being overtopped by the stream. Subsequent debris flows in late spring were caused by high intensity rainfall and large amounts of overland flow. Resultant sudden high stream volumes coupled with high channel resistance encouraged development of a very large wave capable of carrying massive quantities of soil, rocks, and trees.

Another form of mass erosion termed dry creep or dry ravel occurs on steep slopes with soils that are high in coarse materials and low in cohesion. Removal of protective litter by fire allows the soil particles to easily move downslope under the influence of gravity. In western Oregon, dry creep following logging and slash burning ranged from .008 to 1.34 cubic meters per hectare for a 2-year period following disturbance severe enough to bare 55 percent of the soil (Mersereau and Dyrness 1972). No dry creep was observed on nearby undisturbed slopes. Similar results were reported for the San Gabriel Mountains in southern California. Krammes (1963) measured annual dry creep averaging from 0.03 to 0.47 metric tons per hectare. By the end of the third year after the fire, dry creep was reduced to a range of 0.004 to 2.06 metric tons per hectare, presumably in response to regrowth of vegetation.

DOWNSTREAM EFFECTS

TOTAL DISCHARGE, PEAK FLOWS, BASE FLOWS, AND TIMING OF FLOW

Responses of streamflow to the integrated effects discussed in the previous section are: increased peak spring discharge, increased total annual discharge, greater stormflows, and increased baseflow. In California, increased stormflow and baseflow are the principal discharge responses to fire.

In 1970, the first year following wildfire in north central Washington, Helvey (1973) and Helvey et al. (1976) observed a 50 percent greater discharge from burned watersheds than predicted values based on the calibration period. During the second year after fire, snow accumulation was 150 percent greater than normal. This, coupled with greater autumnal soil moisture (Klock and Helvey 1976b), resulted in discharge twice as great as predicted values based on prefire conditions. Discharge was also influenced, an unknown amount, by greater than normal precipitation during 1971. Peak discharge from one watershed was more than double the maximum observed during the 9-year calibration period (Helvey et al. 1976). These burned watersheds were extremely sensitive to individual summer storm events. Discharge after storm events showed increases of 150 to 200 liters per second. Debris flows resulting from unusually early spring warming and high intensity summer rainfall were described in the previous section.

Sinclair and Hamilton (1955) found that stormflow increased threefold to fivefold on a burned California chaparral watershed during the first rainy season following fire. This same watershed produced peakflows that were up to four orders of magnitude greater than the expected peaks during the first major storm of the season. The increase in storm runoff on burned watersheds has also been reported by Rowe et al. (1954), Brown (1972) and Davis (1977).

The Arizona chaparral, counterpart of California watersheds, is also highly responsive to storm events following fire. Stream discharge the first year after wildfire was more than 10 times greater (30.45 centimeters) than prior to fire (2.79 centimeters) with comparable total annual precipitation. Intermittent streamflow prior to fire became continuous following fire except during an extremely dry year (Pase and Ingebo 1965).

Following wildfire in a ponderosa pine ecosystem in Arizona, Campbell et al. (1977) observed an eightfold increase in runoff from a severely burned watershed compared to an unburned watershed during heavy autumn rains. Peak discharge on a severely burned watershed as a result of rainfall was 58 times greater than from the unburned control during the wettest October on record. Average seasonal runoff efficiency (ROE), the ratio of runoff to precipitation, increased from 0.8 percent on an unburned watershed to 3.6 percent on a severely burned watershed. Compared to a moderately burned watershed, ROE on a severely burned watershed was 375 percent greater during the rain season and 51 percent less during the snow season. Rain season differences were attributed to lower tree basal area, reduced litter cover, and hydrophobic soil that may have resulted in lower evapotranspiration rates and more runoff from severely burned than moderately burned watersheds. Campbell et al. speculated that in winter lower tree basal area of a severely burned watershed enhanced evaporation, resulting in less runoff than from a more shaded, moderately burned watershed.

In the second year following wildfire in northeastern Minnesota, Wright (1976) reported that annual runoff into lakes below a burned watershed was 60 percent greater than for an unburned watershed. Although there was no prefire data to support the observed increases, the watersheds were similar in geology, soils, and vegetation. Comparisons with runoff into other lakes in unburned watersheds supported his conclusion that fire resulted in increased flow.

According to Anderson et al. (1976), the 1933 Tillamook burn in Oregon (partly burned again in 1939 and 1945) increased total annual water yield of two large watersheds (366 to 407 square kilometers) by 9 percent or 20 centimeters. Flow increased by 16 to 20 percent or 1.3 to 1.8 centimeters from July through September during the first 16 years after the first fire. Peak annual discharge increased about 45 percent the first year after fire compared to a slightly burned watershed. The peak annual discharge increase declined to 10 percent by the seventh or eighth years.

Crown fire in a ponderosa pine and Douglas-fir forest of Arizona increased peakflows by 5 to 15 times the first summer after fire (Rich 1962). Peakflows continued to be high through the second summer but winter peakflows did not exceed those prior to fire.

Rowe et al. (1954) reported increases in peak discharge that varied from 2 to 45 times normal, depending on storm size, in the first year following fire. The time required for peak discharge to return to normal was from 30 to 70 years, depending on storm size and individual watershed characteristics.

In addition to increased stormflows, there is also evidence that fires increase mean annual baseflow, but this is not well documented. Colman (1953) reported increases in flows during the dry season from a burned watershed (Fish Canyon) in the San Gabriel Mountains of California. Crouse (1961) also reported increased dry-season flows from two burned watersheds in the San Dimas Experiemental Forest (Monroe Canyon and Bell II Canyon). However, Crouse noted, that these watersheds had been previously treated to induce higher discharges, but he felt that the fire of 1960 had made a significant contribution to the increased dry-season flows.

Berndt (1971) observed immediate increases in baseflow rates following wildfire in north-central Washington. In addition, removal of vegetation along stream channels virtually eliminated diurnal oscillations of flow. Baseflow rates persisted above prefire levels through 1973.

Although no publications were found that specifically emphasized timing of discharge as a study objective, earlier peakflows have been observed from burned watersheds (Helvey 1973). Also, the initiation of the spring discharge period occurred earlier than during the calibration period in Helvey's study. He attributed earlier snowmelt and discharge to lower snow albedo caused by dust from blackened timber and increased surface exposure with elimination of the overstory.

WATER QUALITY

Concern for effects of perturbations such as fire on quality of water from wildlands was manifested in Public Law 92-500, the 1972 amendments to the Federal Water Pollution Control Act, and the 1976 National Forest Management Act.

Section 208 of Public Law 92-500 specifically mandates identification and control, to the extent feasible, of nonpoint-source pollutants resulting from silvicultural activities. Public Law 94-588, the National Forest Management Act also specifies that land management plans ensure protection of soil and watershed resources.

Sediment and Turbidity

Sediment and turbidity are the most dramatic and important water quality responses associated with fire. Both are also poorly documented aspects of fire-related watershed research, particularly with respect to origin and delivery rates. Sediment and turbidity result from: overland flow and erosion; channel scouring because of increased discharge and greater stream exploration area; dry ravel and creep accumulations in stream channels; and mass erosion.

Rice (1974) identified the direct sources of sediment produced from Harrow Canyon, California in 1969. This watershed had been burned the previous summer. Rice estimated that 74 percent of the sediment came directly from scour of residual sediment in the Harrow Canyon channel, another 22 percent came from rills and gullies, and very small quantities came from wind, dry ravel, and landslides. He went on to point out that the major sources of sediment produced from the Harrow Canyon channel originated upslope, and estimated that landslides originally contributed 54 percent and dry ravel contributed 33 percent of the sediment.

Values shown in table 1 are indications of nationwide variability of sediment delivery in response to fire. Documentation of the direct causes of these levels and the great differences among levels has been achieved in only a few studies.

Documentation is particularly poor for turbidity responses to fire. Turbidity is a difficult parameter to characterize because it is highly transient and extremely variable. In northern California, mean annual turbidity for all types of land is about 470 parts per million ranging to as great as 2,000 parts per million (Anderson et al. 1976). They reported that logging might increase this range up to eight times, but reported no results of fire-related research in their review. Wright et al. (1976)

Table 1.—*Effects of fire on sediment delivery*

Authors	Habitat	Location	Treatment	Sediment transport Pre-treatment or control	 Post-treatment
				kg · ha⁻¹ · yr⁻¹	
DeByle and Packer (1972)	Western larch, Douglas-fir	Western Montana	Clearcut, slash burned	0[1] 0[2]	168 150
Glendening et al. (1961)	Chapparral	Central Arizona	Wildfire	175	204,000
Wright et al. (1976)	Oak-juniper steep slopes	Texas	Broadcast burn	.02	28
Biswell and Schultz (1965)	Ponderosa pine	California	Understory burn	0[3]	0
Copley et al. (1944)	Southern woodland	North Carolina	Prescribed burn	0	11,200
Meginnis (1935)	Oak-woodland	Mississippi	Harvest, Annual burning	45	740
Krammes (1960)	Chaparral	California	Wildfire	5530	55,300
Campbell et al. (1977)	Ponderosa pine	Northern Arizona	Wildfire	0-3	1-1254

[1] Snowmelt.
[2] Summer storms.
[3] No surface runoff and no erosion observed.

studied effect of slope steepness on turbidity following prescribed fire on dozed juniper lands in central Texas. On level slopes (1 to 4 percent), burning caused no change in turbidity— levels remained at 12 JTU[1]. On moderate slopes (8 to 20 percent) turbidity more than doubled (20 JTU for the control compared to 53 JTU for burned watersheds). On steep slopes (37 to 61 percent), turbidity reached 132 JTU.

Stream Temperature

Water temperature has been shown to change markedly regardless of how shading is removed (Levno and Rothacher 1969, Anderson et al. 1976). Levno and Rothacher (1969) found that maximum weekly water temperature in a western Oregon stream increased 6.7° to 7.8° C in June through August, after logging and slash burning. They also showed that the variability of water temperature following slash burning increased markedly.

Helvey et al. (1976) measured increases in midsummer stream temperatures of up to 12.2°C following wildfire. Maximum water temperature reached 21° C. They also measured the change in temperature as a function of distance from the water source area, topographic effects, and vegetal

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[1] JTU refers to Jackson turbidity units as determined by the nephelometric method. This method uses a comparison of intensity of light scattered by a sample of water relative to the intensity of light scattered by a standard reference suspension under the same conditions (Taras et al. 1971). Current preferred terminology is NTU (Nephelometric turbidity units) which is equivalent to JTU.

shading. At a site near the point where surface water originated, temperature fluctuated through the narrow range of 5.8 to 8.8° C. At a second site, about 1.5 kilometers from the source below a steep gradient on a south aspect, stream temperature fluctuated between 3.4 and 20° C. A third station was in a deeply dissected valley where the stream received considerable topographic shading, as well as some shading from live trees; temperature fluctuated between 4.6 and 15.4° C. The fourth station was below a stream reach that had a steep gradient and virtually no shading; steam temperature ranged from 1 to 21° C. Helvey et al. (1976) concluded that the increased flow rate resulting from reduced evapotranspiration played a secondary, but compensatory role in stream temperature control compared to shade reduction caused by destruction of stream vegetation cover.

Chemical Quality and 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 people-caused disturbance alters the form or distribution of nutrients. Fire exerts profound effects on the nutrient status of plant communities manifested in a rapid mineralization and dispersion of plant nutrients from an intrabiotic to an extrabiotic state. Part of the plant-and litter-incorporated N,P,K,Ca,Mg,Cu,Fe,Mn, and Zn are volatilized and may be evacuated from the system (Allen 1964, DeBell and Ralston 1970, Evans and Allen 1971). Metallic nutrient elements such as Ca,Mg, and K are converted to oxides and deposited as ash on the soil surface. The oxides are low in solubility until they react with CO_2 and H_2O of the atmosphere and are converted to bicarbonate salts. In this form, they are substantially more soluble and vulnerable to loss via surface runoff and leaching than as oxides or incorporated in plant tissues and litter. Reduced plant cover in the postfire situation increases erosion susceptibility of nutrients. Severing soil-plant cycling mechanisms reduces uptake opportunity for nutrients and further increases the potential for nutrient loss by leaching.

Above normal movement of nutrients to streams via surface erosion and leaching has the potential for impairing quality of surface water for municipal purposes, causing eutrophication of aquatic habitats, and lowering site productivity.

Bicarbonate Responses to Fire

There is general agreement among studies that bicarbonate in soil solution and in streamflow is increased as a consequence of burning (Grier and Cole 1971, Fredriksen 1971, DeByle and Packer 1972, Snyder et al. 1975, Longstreth and Patten 1975, Kimmins and Feller 1976, Tiedemann et al. 1978). McColl and Cole (1968) showed that the bicarbonate ion is the principal anion in the soil solution. Bicarbonate 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 principal carrier of cations in the soil solution.

Nitrogen Responses

Nitrate-N (NO_3-N), ammonium-N (NH_4-N), and organic-N (O-N) (measured as Kjeldahl-N) are the nitrogen forms most commonly studied as indicators of effects of disturbance or land management activity on water quality. Nitrate-N has been emphasized because it is one of the most mobile ions in soil-water systems, has a recommended standard of 10 milligrams per liter maximum of N as nitrate (Environmental Protection Agency 1973), and is one of two forms of N used by plants.

Nitrogen concentrations are normally at very low levels in streams from undisturbed areas. Reported values of NO_3-N ranged from less than 0.01 milligrams per liter (Fredriksen 1971, Tiedemann 1973, Helvey et al. 1976) to 1.2 milligrams per liter (Brown et al. 1973).

Response of nitrogen to burning was quite varied among studies. Lotspeich et al. (1970), Wright (1976), and McColl and Grigal (1977) found no change in surface water (stream or lake) levels of nitrate- or organic (Kjeldahl)-N. However, in several studies, nitrate-N was shown to increase in either soil solution (Viro 1974, Knighton 1977) or in streamflow following fire (Fredriksen 1971, Brown et al. 1973, Tiedemann 1973, Longstreth and Patten 1975, Kimmins and Feller 1976, Helvey et al. 1976, Tiedemann et al. 1978). Although striking increases in maximum NO_3-N levels were observed following fire, none exceeded the recommended Environmental Protection Agency (1973) level of 10 milligrams per liter.

Maximum reported levels of NO_3-N in response to fire ranged from 0.43 milligrams per liter (Fredriksen 1971) to 7.6 milligrams per liter

Table 2.—*Effects of fire and selected treatments on maximum NO_3-N concentration in streamflow*

Author	Habitat	Location	Treatment	Maximum NO_3-N Pre-treatment or control	 Post-treatment
				mg/liter	
Brown et al. (1973)	Douglas-fir, Red alder	Western Oregon	Clearcut, slash burned	0.7	2.1
Fredriksen (1971)	Douglas-fir	Western Oregon	Clearcut, slash burned	0.1	.43
Likens et al.[1] (1970)	Eastern deciduous forest	Northern New Hampshire	Clearcut, herbicide treatment	2.5	82.0
Hibbert et al. (1974)	Chaparral	Central Arizona	Herbicide treatment	.2	56.0
Hetherington (1976)	Engleman spruce, Subalpine fir	Eastern B.C., Canada	Clearcut	.02	0.4
Johnson and Needham (1966)	White-fir, Ponderosa pine	Central California	Wildfire	.01	.01
Tiedemann et al. (1978)	Douglas-fir, Pinegrass	Eastern Washington	Wildfire	.02	.6
Tiedemann et al. (1978)	Douglas-fir, Pinegrass	Eastern Washington	Wildfire, nitrogen fertilization	.02	1.5
Hoffman and Ferreira (1976)	Mixed conifer shrub	Central Sierra Nevadas	Wildfire	.06	.3
Longstreth and Patten (1975)	Chaparral	Central Arizona	Wildfire 1959, maintained in grass cover	.1	2.0
Snyder et al. (1975)	Western white pine, Western red cedar	Northern Idaho	Clearcut burned	0.8	7.6

[1] Value expressed is for nitrate, not nitrate-N.

(Snyder et al. 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) (Rode 1955). Nitrate moves with moisture through the soil profile to streams.

Ammonium-N levels in stream water were reported in three studies. Fredriksen (1971) found increased levels of NH_4-N only within the first 2 weeks following a slash fire. Maximum levels exceeded recommended limits of 0.5 milligrams per liter by more than 10 times. Tiedemann (1973) found no change in stream levels of NH_4 -N following wildfire but sampling was not initiated in this study until 6 weeks after fire. Hoffman and Ferreira (1976) noted increased NH_4-N in stream water immediately below a burned area (0.1 milligrams per liter) compared to a site above the burn (0.03 milligrams per liter).

Organic-N (O-N) also increased in response to burning (Hoffman and Ferreira 1976, Tiedemann 1973, Helvey et al. 1976, Tiedemann et al. 1978). Concentrations of O-N in streams from burned areas were generally found to be about double the levels prior to fire or in streams from undisturbed areas. Displacement of organic detritus from the stream area because of increased flow and increased stream source area was probably the primary reason for increased O-N (Tiedemann et al. 1978).

Increased flow and increased concentrations of nitrogen in streamflow from burned areas has resulted in accelerated loss of nitrogen. Frederiksen (1971), estimates that combined solution loss of NH_4-N and NO_3-N the first year after slash burning was 2.2. kilograms per hectare per year compared to pre-treatment loss of 0.06 kilograms per hectare per year (table 3). Brown et al. (1973) found that NO_3-N losses increased from pre-treatment levels of 3.2 to 5.5 kilograms per hectare per year to more than 16 kilograms per hectare per year. They concluded that these losses posed no threat to continued site productivity. Losses of NO_3-N increased from 0.5 kilograms per hectare per year to 5.1 kilograms per hectare per year in a study of clearcutting and slash burning in western Canada (Kimmins and Feller 1976). Most studies did not place losses in perspective to total site capitals. Streams draining the burned watersheds of the Entiat Experimental Forest in Washington transported nearly 7 kilograms per hectare of N in 5 years (Tiedemann et al. 1978). This was approximately 0.5 percent of the total N capital of the upper 36 centimeters of soil of the watersheds, but

Table 3.—*Effects of fire and selected treatments on solution transport of nitrogen*

Authors	Habitat	Location	Treatment	Solution transport of nitrogen: Pre-treatment or control	Post-treatment
				kg · ha^{-1} · yr^{-1}	
Brown et al. (1973)	Douglas-fir, Red alder	Western Oregon	Clearcut, slash burned	5.0	16.0
Fredriksen (1971)	Douglas-fir	Western Oregon	Clearcut, slash burned	.03	2.1
Likens et al. (1970)	Eastern deciduous forest	Northern New Hampshire	Clearcut, herbicide treated	3	147
Kimmins and Feller (1976)	Western Hemlock, Douglas-fir	Western B.C., Canada	Clearcut	+1.9	5.1
Tiedemann et al. (1978)	Douglas-fir, Pinegrass	Eastern Washington	Wildfire	< .01	3.0
Tiedemann et al. (1978)	Douglas-fir, Pinegrass	Eastern Washington	Wildfire, nitrogen fertilization	< .01	4.1

likely represents a somewhat higher percentage of the available N capital.

Phosphorous Responses

Phosphorus in soil solution, stream waters, and lakes is present mainly in two forms—ortho phosphate (inorganic) 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). Interest in phosphorus has been spurred by knowledge of its eutrophying effects in areas where large quantities emanate from sewage treatment plants as a result of high phosphate detergents.

Some studies of soil leachates showed increased levels of total P after burning, indicating accelerated mobilization of P (Smith 1970, McColl and Grigal 1975, Knighton 1977).

DeByle and Packer (1972) reported increased mobilization of T-P in runoff from clearcut and burned areas. McColl and Grigal (1975) and Gifford et al. (1976) found that T-P increased in overland flow from burned areas. However, increases were not sufficient to alter quality of stream or lake water. Stark (1977) found increased concentrations of T-P in soil water from 0 to 55 centimeters with hot burns (>300° C at the soil surface) compared to light burns (200 to 300° C). She concluded that these patterns of elemental concentrations were related to the quality of ash produced, which was a function of burn intensity.

Grier and Cole (1971), in contrast, found that T-P concentrations were highest in leachates of a lightly burned plot (41° C at 2.5 centimeters soil depth) and lowest in a heavily burned treatment (84° C at 2.5 centimeters soil depth). Several watershed studies (Lotspeich et al. 1970, Fredriksen 1971, Brown et al. 1973, Longstreth and Patten 1975, McColl and Grigal 1975, Kimmins and Feller 1976, Wright 1976) have shown that fire does not affect stream water PO_4-P levels. In contrast to results of these studies, Tiedemann et al. (1978) found that T-P levels in streams from burned watershed were 2 to 3 times greater than in a stream from an unburned watershed. Lotspeich (1972) found a temporary increase in T-P in a stream in Alaska as the result of the use of 228,000 liters of fire retardant.

Phosphorus transport in solution was not large for any of the studies where this was determined. Fredriksen (1971) reported an increase in solution loss from 0.13 to 0.49 kilograms per hectare per year following burning. Wright found increased transport of P in runoff from 1.5 milligrams per square meter per year to 3.6 milligrams per square meter per year (0.015 to 0.036 kilograms per hectare per year) following wildfire in Minnesota. Tiedemann et al. (1978) did not measure prefire or first and second year T-P losses but during the third to fifth year after wildfire, losses ranged from 0.06 to 0.15 kilograms per hectare per year. The accumulated loss represented 0.01 percent of the site nutrient capital for P.

Cation Responses

Cations are perhaps the best studied of chemical water quality constituents. As pointed out earlier, fire substantially alters the form and distribution of cations, placing them in a vulnerable position for removal by runoff and leaching.

Responses of cations to fire are difficult to interpret because of differing amounts of plant biomass and litter, differential fire intensity, the exchange capacity of humus and soil, and moisture flux and timing. All studies of soil solutions and surface runoff following fire indicated increased levels of cations such as Ca, Mg, K, Na, and Mn (Smith 1970, Grier and Cole 1971, DeByle and Packer 1972, Lewis 1974, Gifford et al. 1976, Knighton 1977, and Stark 1977).

From the standpoint of stream water quality and site productivity, these studies did not indicate the potential for movement of cations through the soil profile to ground water and eventually to stream and lake systems. However, Grier (1975), demonstrated that an intense fire in central Washington produced an average ash weight of 2,900 kilograms per hectare. The ash layer contained 314 kilograms per hectare of Ca, 54 kilograms per hectare of Mg, 70 kilograms per hectare of K, and 22 kilograms per hectare of Na.

Leaching of the ash layer in the first year after burning transferred 149 kilograms per hectare of Ca, 50 kilograms per hectare of Mg, 92 kilograms per hectare of K, and 33 kilograms per hectare of Na from the ash layer to the soil. Of the amounts leached from the ash, 134 kilograms per hectare of Ca, 48 kilograms per hectare of Mg, and 84 kilograms per hectare of K were retained in the 0- to 19-centimeter layer of soil. In the same interval a net loss of 29 kilograms per hectare of Na was observed from the 0- to 19-centimeter layer of soil.

Cation leaching from ash layers was primarily related to water percolation through the ash. Grier's results indicated that in this particular case, the soil system maintained a high degree of retentive power for cations.

Stark (1977) demonstrated a difference in cation loss from soils between hot burns (>300° C at the soil surface) and cooler burns (200 to 300° C). Net losses of Ca and Mg occurred below the root zone when soil surface temperatures exceeded 300° C. Iron, in contrast, declined in leachates as fire temperature increased. Response of iron may thus be a good indicator of effects of fire on soil cations. Stark observed that losses of Ca were balanced by inputs from precipitation in the absence of fire. Cooler burns caused no transport of ions out of the rooting zone compared to control plots.

Using a biological life equation for calculating the time a soil can continue to provide adequate levels of nutrients for plant growth, Stark speculated that chemically fragile soils might not withstand repeated burning at temperatures in excess of 300° C because of mobilization of Ca and Mg and transport out of the soil profile.

DeByle and Packer (1972) studied plant nutrient concentrations and losses in overland flow and sediment from burned forest clearcuts in larch/Douglas-fir forest habitats of western Montana using small runoff plots. Concentrations of Ca, Mg, and Na in surface runoff were greater than baseline levels for the first and second years after fire. Although combined losses of Ca, Mg, Na, and K on sediment and in solution from burned plots were greatly increased compared to controls, they concluded that losses were an insignificant proportion of the available soil capital of those nutrients.

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 fire on ionic composition and concluded that increased runoff resulting from transpiration reduction masked concentration effects (table 4). Stottlemeyer and Ralston (1968), Tiedemann (1973), Synder (1976), Helvey et al. (1976), and Tiedemann et al. (1978) observed that concentration of major cations was inversely proportional to flow. McColl and Grigal (1977), in contrast, found significantly increased concentrations of K that were attributed to an interaction of fire and soils derived from lacustrine glacial sediments. Snyder et al. (1975), in contrast to the other results of Snyder (1976), observed that K, Ca, and Mg were

Table 4.—*Effects of fire and selected treatments on concentration of major cations (Ca, Mg , Na, and K) in streamflow*

Authors	Habitat	Location	Treatment	Cation concentration	
				Pre-treatment or control	Post-treatment
					mg/liter
Fredriksen (1971)	Douglas-fir	Western Oregon	Clearcut, slash burned	5.9	10.7
DeByle and Packer (1972)	Western larch, Douglas-fir	Western Montana	Clearcut, slash burned	218.0	130.0
Tiedemann et al. (1978)	Douglas-fir, pinegrass	Eastern Washington	Wildfire, nitrogen fertilization	13.0	9.0
Likens et al. (1970)	Eastern deciduous forest	Northern New Hampshire	Clearcut, herbicide treatment	3.2	13.6
Synder et al. (1975)	Western white pine, western red cedar	Northern Idaho	Clearcut, slash burned	7.4	13.2
Longstreth and Patten (1975)	Oak chaparral	Central Arizona	Wildfire maintained in grass cover	66.0	51.0

Table 5.—*Effects of fire and selected treatments on solution loss of major cations (Ca, Mg, Na, and K) in streamflow*

Authors	Habitat	Location	Treatment	Solution transport of cation: Pre-treatment or control	Solution transport of cation: Post-treatment
				kg · ha^{-1} *· yr*$^{-1}$	
Fredriksen (1971)	Douglas-fir	Western Oregon	Clearcut, slash burned	46	133
DeByle and Packer (1972)	Western Larch, Douglas-fir	Western Montana	Clearcut, broadcast, slash burned	1.5	8.2
Tiedemann et al. (1978)	Doublas-fir, pinegrass	Eastern Washington	Wildfire	15	63
Likens et al. (1970)	Eastern deciduous forest	Northern New Hampshire	Clearcut, herbicide treated	27	168
Kimmins and Feller (1976)	Western hemlock, Douglas-fir	Western B.C., Canada	Clearcut, calcium only	23[1]	140
DeBano and Conrad (1978)	Chaparral	Southern California	Prescribed fire	0[2]	34

[1] Calcium values only were reported.

[2] Trace.

higher in stream water at a burned site than at a point above the burn (table 4). Below the burn, and after passage through a buffer strip, there were only slight differences in Ca and Mg compared to the stream location above the burn. Maxima and mean concentrations of Ca, Mg, and K increased following slash burning in western Oregon (Fredriksen 1971). Similarly, Ca and K concentrations increased after burning in chaparral (Longstreth and Patten 1975).

From the variability of responses exhibited by cations among the various studies, it is apparent that we presently have insufficient information to adequately predict effect of fire on concentrations of cations in streamflow.

Solution losses of cations were substantially greater than those of N or P. Wright (1976) noted that K losses increased by 263 percent following fire in Minnesota. Fredriksen (1971) found that annual losses of the four major cations more than doubled the first year following fire (from 56 to 133 kilograms per hectare for a control and burned area, respectively) (table 5).

In streams from the burned Entiat Experimental Forest in Washington, cation losses doubled between the first and second years after fire—31.9 compared to 61.1 kilograms per hectare per year. Tiedemann et al. (1978) found that this increase was larger than the comparison of prefire losses with first year losses (19.3 to 31.9 kilograms per hectare per year) (Tiedemann and Helvey 1973). Greater flux of moisture in the second year after fire was primarily responsible for increased loss. The cumulative solution loss of 5 postfire years comprised 17, 13, 4, and 39 percent of the available capitals of Ca, Mg, K, and Na respectively in the upper 36 centimeters of soil. Immediate and long-term site productivity effects of these losses were not determined.

Sediment Losses of Nutrients

Loss of nutrients attached to sediment and as an integral part of sediment is receiving increased attention because sediment is still the major nonpoint-source pollutant problem on wildlands. Concern focuses on effects of nutrients on aquatic habitats and the consequences of losses to upslope site productivity.

Frederiksen (1971) computed losses of nutrients on sediment and in suspended organic material (table 6). Sediment losses of nutrients from burned

Table 6.—*Sediment transport of nitrogen from logged and burned watersheds*

Authors	Habitat	Location	Treatment	Total N lost	
				Pre-treatment or control	Post-treatment
				$kg \cdot ha^{-1} \cdot yr^{-1}$	
Fredriksen (1971)	Douglas-fir	Western Oregon	Clearcut, slash burned	.16	3.8
DeByle and Packer (1972)	Western larch, Douglas-fir	Western Montana	Clearcut, slash burned	0	9.5
DeBano and Conrad (1978)	Chaparral	Southern California	Prescribed fire	0[1]	15.1

[1] Trace.

Table 7.—*Sediment transport of cations after fire*

Authors	Habitat	Location	Treatment	Cation[1] transport	
				Pre-treatment or control	Post-treatment
				$kg \cdot ha^{-1} \cdot yr^{-1}$	
Brown et al. (1973)	Douglas-fir	Western Oregon	Clearcut, slash burned	.3	5.6
DeByle and Packer (1972)	Douglas-fir	Western Montana	Clearcut, slash burned	0	37
Debano and Conrad (1978)	Chaparral	Southern California	Prescribed fire	0[2]	131

[1] Ca, Mg, Na, and K.
[2] Trace.

areas increased strikingly the first and second years after burning compared to controls but were in the same order of magnitude as solution losses for N and much lower than solution losses for major cations. DeByle and Packer (1972) reported solution and solution-plus-sediment losses of nutrients after logging and burning in western Montana. They found that sediment was the primary source of loss for P, Ca, Mg, and K (tables 5 and 7) whereas Na losses were mostly in solution.

In California chaparral, DeBano and Conrad (1978) found that sediment losses of N, P, and cations after wildfire substantially exceeded those lost in solution (tables 5, 6, and 7). For N and P, sediment losses were 15.1 and 3.4 kilograms per hectare contrasted to only trace amounts of solution loss. Loss of Ca, Mg, Na, and K in solution was about one-fourth of the loss on sediment (tables 5 and 7). However, sediment and solution losses of nutrients comprised only a minor proportion (0.7 to 8 percent) 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

We are accumulating an adequate data base of effects of fire on nutrients and stream water chemistry but attendant responses at the stream level have not been well studied. Lotspeich et al. (1970) studied stream macroinvertebrate responses to wildfire in Alaska. They concluded that changes in the chemical makeup of the water were below the magnitude to exert an impact on the aquatic organisms they studied.

Hoffman and Ferreira (1976) examined periphytic algae above and below burned sites and found essentially no difference in the similarity index, indicating that water quality changes did not exert any measurable effect on algae growth. The same results were obtained for benthic macroinvertebrates. Wood (1977) was unable to demonstrate any significant changes in species diversity or numbers of aquatic macroinvertebrates when streams were exposed to clearcutting and slash burning.

Forthman followed changes in water chemistry for 28 hours after prescribed burning in a 3-m stand of sawgrass standing in 30 centimeters of water.[2] Fuel consumption averaged 14.96 metric tons per hectare and resulted in immediate statistically significant increases in concentrations of PO_4-P (0.01 to 0.83 milligrams per liter) and K (2.8 to 4.3 milligrams per liter). Nitrate-N increased slightly from 0.03 to 0.06 milligrams per liter. There were significant increases in PO_4-P concentrations at the control sites within the next 6 hours, which she attributed to the deposition of ash from the smoke plume. All concentrations on all sites had returned to preburn levels within 28 hours after the fire. This rapid decrease suggested that direct uptake of these nutrients by micro-organisms might be responsible.

Yates concluded that the increased periphyton production she documented after a sawgrass *(Cladium jamaicense* Crantz) fire was due to the increased amount of sunlight reaching the water surface.[3] Wood and Maynard (1974) monitored Everglades microalgae at several sites over a 3-year period. One site was established immediately after a dry season fire in sawgrass on marl soil. The algal mat was badly scorched and appeared completely desiccated, but laboratory cultures proved many of the microalgae were still viable. Regeneration of the algal mats and periphyton on the area began as soon as sufficient moisture was available. After 6 months, both the diversity and biomass became dependent upon water levels. A total of 52 species of diatoms were recorded in the 7-month period following the fire which compared favorably with the unburned sites (Wood and Maynard 1974).

Steward and Ornes (1975a) enriched a sawgrass community with 22 weekly additions of a distilled water solution of NaH_2PO_4. Dense continuous algal blooms began the fourth week. As the algal growth rate leveled off 3 weeks later, dissolved P began to increase in the water samples. Sawgrass began accumulating P the fourth week but growth rates never increased, indicating that this P assimilation was simply luxury consumption. These investigators also reported dynamic shifts in phytoplankton genera and the disappearance of two aquatic macrophytes, presumably because the algal blooms decreased the sunlight penetrating the water. Although fire would result in a single dose rather than weekly additions, it is conceivable that organic soil fires could result in the release of a comparable total amount. Although not often documented, dense algal blooms have been observed after severe wildfires in the Everglades. In fact, in the course of the above study by Steward and Ornes (1975b), many of their control plots were destroyed by a dry season wildfire. Changes in algal species or growth rates were not mentioned but they reported that 2 months after fire, sawgrass regrowth had accumulated large amounts of both phosphorous and potassium. Sawgrass was well adapted to withstand fire because it rapidly developed rhizomes and outcompeted other species that were intolerant of shade.

In the warm shallow waters of Florida, aquatic habitat responses assume major importance. Here millions of acres of organic soil support marsh and swamp ecosystems that cycle between flood and drought conditions. During the annual 6 to 7 month south Florida dry season, the water table often drops below ground level in the Everglades, allowing the organic soils to dry to the point where they become combustible. Fires during prolonged droughts can consume peat on muck layers several feet thick, releasing stored nutrients in a matter of days. These fire-created depressions will fill with water the next rainy season. Thereafter, they not only provide dry season feeding sites for birds and animals, but they become refugia for many aquatic species and act as recolonization centers when the region floods again (Robertson 1953, Loveless 1959).

Very little is known concerning fire-algae relationships and their significance in south Florida. However, periphyton probably is a significant primary producer and important link in the food chain as well as being the source of the calcitic mud, which is the second most abundant sediment in the Everglades (Gleason and Spackman 1974).

Algal blooms following wildfire occur in other areas of the South as well. Odum et al. (1975) documented the aftermath of an organic soil fire in a north Florida cypress stand. Soon after surface water returned, a floating algal mat appeared followed by a thick cover of duckweed. Oxygen level dropped to near zero in the water. Nitrogen also became depleted, possibly because of denitrification by microbes in the anaerobic water and because of uptake by the duckweed growth.

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[2] Forthman, Carol Ann. 1973. The effects of prescribed burning on sawgrass (*Cladium jamaicense* Crantz) in south Florida. M.S. Thesis, Univ. of Miami, Coral Gables, Fla. 70 p. illus.

[3] Yates, S.A. 1974. An autecological study of sawgrass, *Cladium jamaicense* Crantz, in southern Florida. M.A. Thesis, Univ. of Miami, Coral Gables, Fla. 117 p. illus.

Intrusion of salt water into fresh water areas where creek or river embankments have been burned through has been documented as an important effect of fire in the lower Everglades. Existing vegetation is killed and halophytic species predominate.

RESEARCH NEEDS AND PRIORITIES

An assessment of research needs and priorities is outlined in table 8. To avoid duplication of effort, the work group determined research needs and priorities for downstream effects before those for onsite effects. Downstream needs and priorities were then used to indicate importance of studying individual onsite hydrologic responses to fire. For example, water yield as a downstream effect of fire has low priority for research, primarily because of our current level of knowledge and confidence in our ability to relate what is known to fire situations. Thus, for onsite effects, evapotranspiration, one of the principal parameters of water yield, assumed low priority.

It was the consensus of the work group that a separation be made for effects of wildfire and effects of prescribed fire. Prescribed fire plans normally include protection of the water resource and the aquatic habitat; therefore, the effects on water would be expected to be generally of lower magnitude than with wildfire.

It was also the consensus of the work group that wildfire effects should be considered separately from those resulting from wildfire suppression and rehabilitation activities. Suppression activities are sometimes conducted with little concern for watershed stability, water quality, or aquatic habitat consequences. In some cases, damage from suppression activities may exceed those resulting from fire itself.

Rehabilitation is addressed as a separate and moderating influence of fire, although some activities such as fertilization have a potential for exerting adverse water quality consequences.

Priorities are a subjective assessment based on: current level of knowledge, confidence with which current knowledge can be extrapolated to a wide range of biogeographical settings, and the need to know—how important was the information to current and long-range objectives of the research and wildland management communities?

DOWNSTREAM EFFECTS

Water yield (low priority)—The range of effects is generally known for most areas of the United States. Thus, it should be possible to predict consequences of fire with reasonable accuracy. Alaska is an exception, since very little information exists on water yield responses, and it is not likely that information from other parts of the United States could be applied; therefore, the priority in Alaska is probably moderate or high.

Timing (low priority)—Capability for extrapolation from existing information should be good. It should be recognized, however, that data may not be exactly applicable to prescribed fire.

Peakflows (high priority)—Effects of fire, particularly prescribed fire, are very likely to be different from effects of timber harvest. There is substantial information for wildfire; therefore, the priority would be moderate. An urgent need exists for information on effects of suppression activities and effectiveness of rehabilitation prescriptions in reducing peakflows.

Chemistry (low to moderate priority)—Effects of wildfire and some types of prescribed fire on stream chemistry are becoming adequately documented. An exception is the Northeastern United States where chemical water quality persists as a major problem. Chemical water quality may also be of higher priority in the Southeastern United States. Wildfire suppression is rated at low priority because this activity does not normally affect enough area to cause changes in chemical loading of streams. However, there may, be a need to know more about effects of suppression retardants on water chemistry.

Temperature (low to moderate priority)—Temperature changes in response to stream exposure can presently be predicted with reasonable accuracy. However, effects of fire, and especially wildfire, may be more extreme than logging—resulting in the moderate priority rating for wildfire. The priority for prescribed fire is low because the riparian area and aquatic environment are normally protected.

Channel conditions (high priority)—Effects of fire on channel conditions are poorly documented. Knowledge of this aspect of fire is essential for understanding of effects of fire on sediment and

Table 8.—*Research needs and priorities*[1]

	Prescribed fire	Wildfire	Suppression	Rehabilitation
	Downstream Effects			
Physical Hydrology				
Water yield	L	L	L	L
Timing	L	L	L	L
Peakflow	H	M	H	H
Water Quality				
Sediment	H	H	H	H
Chemistry (nutrients)	M	M	L	M
Temperature	L	M	L	L
Channel conditions	H	H	H	H
	Onsite Effects			
Hydrologic process				
Infiltration (overland flow)	H	H	H	H
Evapotranspiration	L	L	L	M
Soil water storage	H	H	H	H
Snow accumulation and melt	M	M	L	L
Soil erosion and deposition (sheet, creep, rill, gully)	H	H	H	H
Land slides	H	H	H	H
Permafrost	H	H	H	H
Nutrient cycling[2]				

[1] H=High, M=Moderate, and L=Low.
[2] Priorities not established (see Effects of Fire on Soil, GTR WO-7).

the aquatic habitat. Little is known of effects of suppression activities or effectiveness of rehabilitation procedures.

ONSITE

Infiltration (high priority)—Infiltration is an important determinant of overland flow, erosion, channel condition, mass erosion, and sediment in streams. It is an element for which we need commonality among studies with respect to specific parameters to measure.

Evapotranspiration, including interception (low to moderate priority).—Reasonably adequate documentation exists from watershed studies. However, there is a need to know more about evapotranspiration responses to fire consumption of moss layers in black spruce forests of

Alaska and evapotranspiration responses to burning sawgrass over water in the Southern United States.

Soil water storage (high priority)—Soil water storage is one of the critical elements of surface and mass erosion responses to fire.

Snow accumulation and melt (low to moderate priority)—Substantial information exists estimating magnitude of effect for these processes from forest harvest. Application of existing information to the fire situation should be reliable. An exception may be the western Cascades of Oregon where rain on snow events are a principal source of erosion.

Soil erosion (high priority)—Erosion is the contributor to sediment degradation of water quality and is a mechanism for loss of nutrients from wildland sites. Little information exists on effects of fire on the actual erosion process and contributory factors. Information is also sparse for effects of suppression activities on erosion and effectiveness of rehabilitation measures for ameliorating erosional consequences of fire.

Landslides (high priority)—Fire has been shown to exert a pronounced effect on land stability. However, there is an urgent need for information on processes involved, and for ways to improve land stability following fire. Effects of suppression activities on landslides are also a poorly studied topic.

Permafrost (high priority)—Disturbance of permafrost is apparently one of the principal contributors to erosion in Alaska. Considering the total area involved, this is an extremely important problem in the United States.

Nutrient cycling.—Since this topic is covered in the Effects of Fire on Soil: A State of Knowledge Review, GTR WO-7, the priority was not established. However, one area of overlap that is of moderate priority is the relationship of nutrients transported offsite by water and sediment to site productivity.

SUMMARY

Although effects of fire on water resources vary widely across the United States, there were some common responses among studies that are worthy of emphasis:

(1) Fire exerts pronounced effects on basic hydrologic processes, leading to increased sensitivity of the landscape to eroding forces and to reduced land stability. This is manifested primarily as increased overland flow, and greater peak and total discharge. These provide the transport force for sediment from the landscape.

(2) Erosion responses to burning are a function of several factors including: degree of elimination of protective cover; steepness of slopes; degree of soil nonwettability; climatic characteristics; and rapidity of vegetation recovery.

(3) Sedimentation, increased turbidity levels, and mass erosion appear to be the most serious threats to water resources following fire (especially wildfire). Elimination of protective streambank cover has been shown to cause temperature increases that might pose a threat to aquatic life.

(4) Despite the lack of documentation of fire size and intensity, large fires of high intensity appear to have the greatest potential for causing damage to water resources.

(5) Fire causes rapid mineralization and mobilization of nutrient elements that are manifested in increased levels of nutrients in overland flow and in soil solution. Watershed studies, however, indicate that these additional nutrients do not significantly impair the quality of surface waters for municipal purposes. Effects of nutrient losses via sediment and solution have not been related directly to site productivity but in general do not appear to represent a significant proportion of total site nutrient capitals.

(6) Fire-caused water quality changes were not shown to adversely affect composition or productivity of benthic macroinvertebrates but this is a poorly documented research area.

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