# Fire Effects on Water Supply, Floods, and Sedimentation

HENRY W. ANDERSON[1]

MANY forest types owe their origin, perpetuation, and distinctive characteristics to fire. What may be called the normal hydrologic behavior of many forested watersheds already incorporates some effects of fire—both natural and man-induced. Fire may have a greater effect than harvesting on peak flows, erosion, and water quality. The protective influence of the forest may be destroyed, slope instability augmented, and channel banks subjected to scour. How we choose to use fire as a tool and how we manage our forests for fire prevention and control depends in part on the consequences of fire to water supply, floods, and sedimentation.

Burning the forest can increase both water yield and streamflow discharge. The amount of increase will depend on the intensity, severity, and frequency of fire occurrence and on the proportion of the watershed burned. Where much of the foliage is destroyed, interception and evapotranspiration will be reduced. And where the organic layers of the forest floor are consumed and mineral soil exposed, infiltration and soil water storage capacities may be reduced.

Soil-water storage capacity is reduced by fire if the humus layers and organic material in the mineral layers are burned, or if exposure of the soil accelerates oxidation of soil organic matter. In the upper

[1]Chief Research Hydrologist, Pacific Southwest Forest and Range Experiment Station, Forest Service, USDA, Box 245, Berkeley, Ca. 94701.

2 inches of soil, severe surface fires can reduce the capacity by about ¼ inch (Dyrness et al., 1957). If the overlying 2-inch layer of humus is destroyed, the reduction would total about 1 inch. Crown fires, obviously, would drastically reduce evapotranspiration and the opportunity for soil-water storage; the result would be similar to clear-cutting the forest. Soil water storage may be reduced by fire-induced repellancy in the surface soil (DeBano, 1968; DeBano and Rice, 1971). At high elevations, forest fires may destroy natural windbreaks, resulting in different snowdrift patterns and changes in water yield (Billings, 1969).

The duration of fire effects ranges from a single season to many decades, depending on the extent of the fire itself and the rate of recovery as influenced by natural conditions, post-fire land use, and remedial measures applied by man. In the East, recovery from fires, usually surface fires, may be rapid, in high elevation areas of the Northwest, regrowth after severe burning can be very slow.

This paper summarizes the effects of fire on water supply and water control in the western timber types, and considers the role of post-fire management.

## ANALYTICAL METHODS

The effects of forest fires on water products from watersheds can be evaluated in one of three ways: The calibrated watershed approach is usually applicable only to controlled burns, for the comparison is with a before-and-after response of a burned and unburned watershed. The second approach, the case study method, is analogous, in which a fire burns one watershed but not another and a relationship can be established between measurements of some hydrologic product before and after the fire. In this method "statistical control" is usually not attempted. The third approach is by model evaluation in which many watersheds with differing amounts of forest fires are evaluated by multivariate analysis, with the effect of the forest fire expressed as proportional change in the hydrologic product. An attempt may then be made to normalize the fire effect on the basis of long-term precipitation or streamflow frequency. Sometimes indexes of fire effects are sought, such as by using runoff plots or transect studies of changes in the soil surface. Each of these approaches has been used in evaluating the fire effects on water products reported here.

## EFFECTS OF FOREST FIRES

### Water Quality

Water quality may be adversely affected by forest fire. Such adverse effects can be illustrated by the damages to water supply of the San Jose Water Works by a fire that swept over 5,610 acres from July 18 to 28, 1961. At the request of the U. S. Attorney the author made a study of the fire effects on water quality and loss of water supply.[1]/ The fire burned some 80 percent of the watershed above the Austrian Dam (Lake Lyman), killing the tops of the brush vegetation and some knobcone pine on the ridges and burning in places under old stands of oak, madrone, and redwood without killing the trees. Water quality both before and after the fire was well monitored. The supply from the reservoir furnished 95 percent of the water service, and the only feasible alternative to use of the water was by pumping from groundwater. Costs were known and fixed. Hence, the three principal types of losses of water due to water quality could be evaluated: (a) loss of overflow of the reservoir because the water was unsuited for use (generally when turbidity was greater than 13 ppm); (b) loss of stored water because of unsuitability; and (c) loss of storage space in the reservoir for future storage of usable water. The amount of such losses (in million gallons) in the 5-year period after the fire totaled 1,372 Mg.:

| | |
|---|---|
| Loss overflow (unsuited) | 424 Mg. |
| Loss stored (unsuited) | 813 Mg. |
| Loss stored (25 yrs., ⅔) | 135 Mg. |

The loss of storage is associated with the historic experience of repeated burns every 50 years (a 2 percent average annual burn); hence, an average expectancy until the next burn is 25 years. Also, the records show that only in 2 years in every 3 was the "lost storage"

[1]/Post-burn hydrology of Los Gatos Creek, affecting watershed and water damages, by Henry W. Anderson, Pac. SW Forest and Range Exp. Sta. File Rpt., 12 p., 1963.

space actually used for water supply. The net damage of 1,372 million gallons necessitated pumping from the groundwater, which was the alternative source of supply, at a cost of $64.67 per million gallons or damage to water supply totaling $88,700. Damage to upstream storage for debris removal was estimated at $64,000, and damages to downstream water quality requiring flocculation of turbidity before percolation to groundwater was $12,500; hence, direct damages to water quality and water supply exceeded $165,000, or about $29.00 per acre burned. This cost is in addition to the cost of fire suppression, post-fire treatments with seeding and check dams, road repair, and managing a fire-damaged watershed for water supply.

Another illustrative case is the Tillamook Burns in coastal forests of northwestern Oregon. Three major fires occurred: the first fire in 1933 burned over nearly 240,000 acres; the second, in 1939, over 189,000 acres; and the third, in 1945, over 180,000. In all 354,939 acres were burned over one or more times. The post-fire treatment consisted of salvage logging 7½ billion board feet, and extensive road building (Bailey and Poulton, 1968). Reforestation began in 1950, with 70 million forest seedlings and nearly 3 billion seeds used to reforest 255,000 acres of the state-owned part of the burned area (State of Oregon, 1973). Annual streamflow, floods, sediment discharge, and frequency of stream turbidity were increased. Let us examine the effect on sedimentation and stream turbidity (1950 sampling), using the sediment concentration-streamflow frequency normalizing technique (Anderson, 1954):

| | Sediment Discharge | Sediment Concentration | Turbidity L.T.13 ppm | | Turbidity G.T.27 ppm | |
|---|---|---|---|---|---|---|
| | T/mi²/yr. | ppm | Days | Water | Days | Water |
| | | | pct. | pct. | pct. | pct. |
| Watershed: | | | | | | |
| Wilson (burned) | 843 | 115 | 38 | 12 | 28 | 72 |
| Alsea (unburned) | 149 | 28 | 90 | 68 | 5 | 20 |

The fire affected various criteria of water quality differently:

Sediment discharge, which serves as the criteria for reservoir damage, was increased 5.7 times. Average sediment concentration, which can be used to compare watersheds with differences in flow—was 4.1 times greater than usual (115 ppm vs. 28). Days that the water was drinkable (less than 13 ppm) were only 40 percent of normal, and the volume of drinkable water only 18 percent as much as before. And lastly, the days that the stream was too turbid to fish (greater than 27 ppm) was 5.6 times more frequent than before (or 84 fewer fishable days per year).

Fredriksen (1970) found that slash burning in October 1966 after logging was completed on a H. J. Andrews Experimental Watershed, in the Cascades of Oregon, consumed all the fine logging debris in the stream channels; soil and rock in the channel released by the fire on the hillside slopes was an additional source of sediment. These combined sources increased suspended sediment concentration by 67 and 28 times the first two years after the burning.

### Chemicals in Streamflow

The effect of forest fires or broadcast burning on dissolved chemicals in streamflow seems to be minimal except where extensive surface erosion is created. Brown et al. (1973) reported that following clearcutting and burning in the Needle Branch stream of coastal Oregon, maximum nitrate nitrogen concentrations increased from 0.70 to 2.10 mg/1. Concentrations returned to prelogging levels by the sixth year after burning. Potassium increased markedly after the burning but reached pre-burn levels again within 2 months. Phosphorus concentrations were unchanged. Brown et al. (1973) concluded that these changes posed no threat to aquatic or terrestrial productivity.

Other investigations have reported similar effects of fire on chemicals in streamflow. Fredriksen (1971) measured loss of nutrients after an old-growth Douglas fir stand was harvested and broadcast burned. Nutrient cations increased by 1.6 to 3 times over that in undisturbed watershed. And a surge of ammonia and manganese exceeded Federal Water Quality Standards for 12 days. Cooper (1969) reported that under unusual torrential rains, fish kills and other detrimental effects resulted from forest fires.

In the part of the Donner Ridge Burn in the Sierra Nevada where a high intensity thunderstorm struck in 1961, Copeland and Croft (1962) found severe soil loss during a storm in which rain fell at the rate of 9 inches per hour for 5 minutes. The storm produced sediment of 1 acre-feet per square mile (Copeland, 1965); thus average sediment concentration exceeded 16,000 ppm. Undoubtedly, significant loss of nutrients and deterioration of water quality for some distance downstream was associated with both the sediment and nutrient content of the runoff. In another part of the burn during the same year, only low-intensity rain and snow fell. Maximum sediment concentration in the streamflow here did not exceed 78 ppm (Anderson, 1962). Johnson and Needham (1966) concluded that in the absence of surface runoff, the acidic nature of forest soil results in dissolved cations being absorbed in the soil exchange complex rather than being washed directly into the stream. As a result, for the years following the fire, no specific effect of the fire on ionic composition of the streams was noted.

DeByle and Packer (1972) in runoff plot studies reported loss of plant nutrients from burned clearcuts in western Montana. The maximum concentration of nutrients in the surface runoff occurred in summer, amounting to only 44 ppm. On the whole, we can agree with Brown (1972) that the effect of forest fire on chemical quality is not the primary cause of deterioration of water quality associated with forest fires in most western forests.

Oxygen or stream temperature rather than nutrient content of streamflow may be the crucial factor in deterioration of water quality as it affects the stream habitat. Krygier and Hall (1967) reported that after the Needle Branch watershed was clearcut and burned, the dissolved oxygen in the stream declined to levels insufficient to sustain fish life. Also water temperatures during the slash fire killed many Coho salmons and cutthroat trout. Monthly maximum water temperatures were increased by as much as 16° during August. Similarly, summer increases in water temperature were also associated with the slash burning in the H. J. Andrews Experimental Watersheds in Oregon. Average maximum water temperatures there increased from 12 to 14 degrees during the period July through August. Maximum stream temperatures reached 75 degrees F., 10 degrees higher than the maximum reported before the watershed was burned (Levno and Rothacher, 1969).

### Annual Streamflow

The Tillamook Burn of 1933 (and partly reburned in 1939 and 1945) in Oregon increased total annual water yield of the Trask and Wilson watersheds (143 and 159 square miles in area). The effect of annual streamflow was evaluated by double-mass analysis with the flow of the unburned Siletz and Youngs watersheds serving as a control:

| | Wilson-Trask | Siletz-Youngs | Diff. | Ratio |
|---|---|---|---|---|
| Years | (inches per year) | | (inches) | |
| 1932, 33 (unburned) | 112 | 112 | 0 | 1.0 |
| 1934-49 | 92 | 83 | 9 | 1.11 |

Thus, the effects of burning on increase in streamflow of 9 inches were about one-half that of the first-year effects of clearcutting on the H. J. Andrews Experimental Forest test (Rothacher 1970). The indicated effect of the Tillamook burns on July-through-September flow from the Wilson and Trask watersheds was an increase of 16 and 20 percent respectively (0.5-0.7 inch) for the first 16 years after the 1933 fire.

The 115,000-acre Entiat Fire of August 1970 in north-central Washington included the Entiat Experimental Forest where water yield and other variables had been measured. Early effects of the fire on streamflow, as reported by Berndt (1971), included a greatly reduced flow rate while the fire was actually burning. Subsequently, the diurnal fluctuation of daily flow declined—a change attributed to destruction of the riparian vegetation along streams—and flows increased. Helvey (1972) reported increases in streamflow averaging 3.5 inches the first year after the fire.

### Peak Flows

Annual peak flows from the Trask and Wilson watersheds were also affected by the Tillamook burns. By comparison with the only slightly burned 200-square mile Siletz watershed, annual peak discharge was increased by about 45 percent the first year after the burn, with the increase declining to 10 percent by the 7th and 8th years after the burn and no indicated increase thereafter.

Snowmelt flood peaks may be increased by burning the shade-producing trees. Burning over one-half of a watershed in the east-side Cascade and Blue Mountain areas of the Northwest increased peaks by about 11 percent (Anderson and Hobba, 1959). Both deliberate broadcast burning and frequent wildfire in logged areas may have contributed to increases from rain-on-snow floods. In Idaho, following the burning of 18 percent of the Clearwater drainage in 1919, spring flood peaks were 11 percent greater and the average peak flow came 14 days earlier. The Columbia River flood in spring 1948 may have been due in part to the large areas of burned-over forest at higher elevations (U. S. Dept. Agr., 1950). At that time, of the 31 national forests which occupied about one-third of the basin, more than 5 million acres were burned—11 percent of the total area. Many of these lands had burned over two or three times in recent times.

The effect of forest fires on streamflow depends on the hydrologic potential of a forest site. This effect can be interpreted from an analysis of watershed models that express site characteristics as variables. To illustrate this concept, I have related four streamflow characteristics to 29 watershed variables.[2/] The data were drawn from 93 watersheds in south coastal and northern California, covering the period 1881 to 1971. The four streamflow characteristics studied were: (a) average annual discharge, (b) average of the maximum daily discharge of a year, (c) 10-year flood, and (d) product of the annual discharge of a year and the maximum daily discharge of that year (called the streamflow sediment-producing potential). The streamflow records were adjusted to the 81-year record by using one of 10 key stations.

A reduction of 2 percent in the average annual burn (a common management objective) can reduce the annual flood by 20 percent, the 10-year flood by 42 percent, and the streamflow sediment

[2/]Anderson, Henry W. The Hydrologic Potential of Unit Areas: A Basis for Managing Water Resources. Water Resources Assoc., 2nd World Congress on Water Resources, New Delhi, India. Proc. Vol. 4, pp. 61-69, 1975.

potential by 41 percent. The quantitative effects depend on the site variables which produce differences of a factor of 10 in the streamflow potential, hence, in the quantitative effect of forest fires. High elevation brushfields in the Sierra Nevada of California have been attributed to spread of fall fires set by sheepmen to "green up" next season's growth. Studies have shown that snow in brushfields melts more rapidly than snow in timber, and thus earlier releases of snowmelt to streams occurs. Slash burning, contrasted with leaving slash untreated after logging at the Swain Mountain Experimental Forest, near Westwood, California, resulted in delayed late season snowmelt of nearly 4 inches (Anderson, 1963).

### Sedimentation

Massive wildfires in humid forest regions have accelerated erosion and sediment deposition. Seventeen years after the Tillamook Burns in the Wilson Watershed of Oregon, the annual sediment discharge rate was 800 tons per square mile, 5 to 8 times that of nearby unburned forested watersheds with similar geology (Anderson, 1954). In the clearcut watershed at the H. J. Andrews Experimental Forest, without roads, for the 1960 through 1968 period, the sediment discharge was 3.3 times that of 307 tons from the undisturbed watershed, with 70 percent of the increase coming after the broadcast burning in 1966 (Fredriksen, 1970). In a study of 23 northern California watersheds, wildfires which averaged 3.4 acres per square mile of watershed, increased suspended sediment discharge by 2.3 times (Wallis and Anderson, 1965). In another study of deposition of sediment in 48 northern California reservoirs, Anderson (1974) found that both current fires and old fires attributed to early graziers augmented deposition by as much as 100 percent for current fires and 55 percent for the old fires. Sartz (1953) measured soil losses that occurred after a wildfire in the Douglas-fir region of the Northwest. Erosion at burned-over transects caused 0.07- to 0.18-foot reductions in the surface soil level (equivalent to 72,000 to 185,000 cubic yards per square mile of area burned). The reduction in soil depth varied directly with differences in the soil slope gradient. However, Sartz suggested that the exposed "shot-loam" soil maintained an infiltration capacity sufficient to prevent most overland flow; growth of vegetation during the first year after the fire provided additional effective control.

## POST-FIRE MANAGEMENT

The hydrologic effects of any post-fire treatments needed to be touched upon here. Natural recovery is sometimes confounded by seeding and planting. Salvage logging may compound the adverse effects of the fire on sedimentation and streamflow turbidity. Reducing fire hazard by falling snags or piling debris and burning may induce instability in surfaces and channels. Seeding of grass on burns may delay tree recovery; the greatest flood discharge in the 1972 Rapid City, S.D. flood was from a partly burned watershed, converted to herbaceous cover, with the peak discharge being twice that of nearby watersheds with similar rainfall (Orr, 1973). Where mechanical control of post-fire runoff and erosion are justified, contour trenches, debris basins, channel armoring, and other treatments may be effective. DeByle (1970) reported only small reductions of peak flows attributable to contour trenching during a long-duration winter rainstorm; whereas a short high-intensity summer storm, which produced flood peak of 2200 cfs/mi$^2$ from a burned but untrenched watershed (Copeland and Croft, 1962), was completely controlled in a trenched watershed (Anderson, 1963).

## CONCLUSIONS

The effects of fire on water in the forest are variable. Light or spot burning, away from channels, have little impact. Wildfires that kill the trees or consume the forest floor and other vegetation over a large area have a major impact on storms, erosion, sedimentation, and quantity of streamflow. The duration of effects is strongly influenced by the rate of revegetation. On the whole, the current level of fire protection has greatly reduced the hydrologic importance of fire as compared to conditions some decades ago. Where severe, widespread wildfire still occurs, as in some areas of the Pacific Northwest, it continues to be a serious threat to water supply and to water and erosion control.

## LITERATURE CITED

Anderson, Henry W. 1954. Suspended sediment discharge as related to streamflow, topography, soil, and land use. Trans. Amer. Geophys. Union 35(2):268-281.

Anderson, Henry W. 1962. Current research on sedimentation and erosion in California wildlands. Int. Assoc. Sci. Hydrol. Publ. 59, p. 173-182.

Anderson, Henry W. 1963. Managing California's snow zone lands for water. USDA, For. Serv. Res. Pap. PSW-6, 28 p. Pacific Southwest Forest & Range Exp. Sta., Berkeley, Ca.

Anderson, Henry W. 1974. Sediment deposition in reservoirs associated with rural roads, forest fires and catchment attributes. Proc. Symp. Man's Effect on Erosion and Sedimentation, Paris, Sept. 9-12, 1974:87-95.

Anderson, Henry W., and Hobba, Robert L. 1959. Forests and floods in the northwestern United States. Int. Assoc. Sci. Hydrol. Publ. 48, p. 30-39.

Bailey, Arthur W., and Poulton, Charles E. 1968. Plant communities and environmental interrelationships in a portion of the Tillamook burn, northwestern Oregon. Ecology 49(1):1-12.

Berndt, H. W. 1971. Early effects of forest fire on streamflow characteristics. USDA Forest Serv. Res. Note PNW-148, 9 p. Pacific Northwest For. & Range Exp. Sta., Portland, Oreg.

Billings, W. D. 1969. Vegetational pattern near Alpine timber as affected by fire—snowdrift interactions. Vegetatio 19(1-6):192-207.

Brown, George W. 1972. Logging and water quality in the Pacific Northwest. Symp. Amer. Water Resources Assoc. Proc. Series 14, p. 330-334.

Brown, George W., Gahler, Arnold R., and Marston, Richard B. 1973. Nutrient losses after clear cut logging and slash burning in the Oregon coast range. Water Resources Res. 9(5):1450-1454.

Copeland, Otis L. Jr. 1965. Land use and ecological factor in relation to sediment yields. U. S. Dep. Agr. Misc. Publ. 970, p. 72-84.

Copeland, Otis L., and Croft, A. R. 1962. The Dog Valley flood of August 12, 1961. J. Geophys. Res. 67(4):1633.

Cooper, Charles F. 1969. Nutrient output from managed forests. In: Eutrophication—Causes, Consequences, Correctives. Nat. Acad. Sci., Washington, D.C. p. 446-463.

DeBano, L. F. 1968. Observation of water repellent soil in western United States. Proc. Symp. Water Repellent Soils, Riverside, Calif. 1968: 17-30.

DeBano, L. F., and Rice, R. M. 1971. Fire in vegetation management—its effect on soil. Proc. Symp. Interdisciplinary Aspects of Watershed Management, Bozeman, Montana, Aug. 3, 1971:327-346.

DeByle, Norbert V. 1970. Do contour trenches reduce wet mantle flood peaks? USDA Forest Serv. Res. Note INT-108, 7 p. Intermountain Forest & Range Exp. Sta., Ogden, Utah.

DeByle, Norbert V., and Packer, Paul E. 1972. Plant nutrient and soil loss in overland flow from burned forest clearcuts. Amer. Water Resources Assoc. Series 14, p. 296-307.

Dyrness, C. T., Youngberg, C. T., and Ruth, Robert H. 1957. Some effects of logging and slash burning on physical soil properties in the Corvallis watershed. U. S. Forest Serv. Pacific Northwest For. & Range Exp. Sta. Res. Pap. 19, 15 p.

Fredriksen, R. L. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds. USDA, For. Serv. Res. Pap. PNW-104, 15 p. Pacific Northwest For. & Range Exp. Sta., Portland, Oreg.

Fredriksen, R. L. 1971. Comparative chemical quality—natural and disturbed streams following logging and slash burning. Proc. Symp. on Forest Land Use and Streamflow Environment, Corvallis, Ore., Oct. 19-21, 1970:125-137.

Helvey, J. D. 1972. First year effects of wildfire on water yield and stream temperature in north central Washington. Amer. Water Resources Assoc. Proc. Series 14, p. 308-312.

Johnson, C. M., and Needham, P. R. 1966. Ionic composition of Sagehen Creek California following an adjacent fire. Ecology 47(4):636-639.

Krygier, James T. and Hall, James D. 1967. Studies of effects of watershed practices on streams. Progress report U. S. Dep. Int. Fed. Water Pollut. Control Admin. Res. Grant WP-432, 95 p.

Levno, Al, and Rothacher, Jack. 1969. Increase in maximum stream temperature after slash burning in a small experimental watershed. U. S. Forest Serv. Res. Note PNW-110, 7 p. Pacific Northwest For. & Range Exp. Sta., Portland, Oregon.

Orr, Howard K. 1973. The Black Hills (South Dakota) flood of June 1972—impacts and implications. USDA For. Serv. Gen. Tech. Rpt. RM-2, 12 p. Rocky Mountain Forest & Range Exp. Sta., Ft. Collins, Colo.

Rothacher, Jack. 1970. Water yield increases following clearcut logging in the Pacific Northwest. Water Resources Res. 6(2):653-658.

Sartz, Richard S. 1953. Soil erosion on a fire-denuded forest area in the Douglas-fir region. J. Soil and Water Conserv. 8:279-281.

State of Oregon. 1973. Tillamook state forest. The Forest Log, Oregon Dep. Forestry, Salem, Oregon, 4 p.

U. S. Department of Agriculture. 1950. How forest conditions affected the 1948 Columbia flood. Agr. Inform. Bull. 10, 17 p.

Wallis, James R., and Anderson, Henry W. 1965. An application of multivariate analysis to sediment network design. Int. Assoc. Sci. Hydrol. Publ. 67, p. 357-378.