

Estimating Hydrologic Values for Planning Wildland Fire Protection¹

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Among the principal criteria for planning a system of wildland fire protection are measures of the values being protected. In addition to human occupancy and improvements, these values include timber, range, wildlife and wildlife habitat, recreation, and watershed or hydrologic values. The cost of protecting these values is related to the economic and social benefits expected from them, the net effects that wildfire would have upon them in the absence of protection, the changes in fire effects that can be achieved by various levels and practices of fire protection, and, of course, the people's ability and willingness to pay for protection (Phillips 1977).

The expected net effects of wildfire on hydrologic values in a watershed are proportional to (a) the hydrologic potential values in the watershed in the absence of fire, (b) the probability of fires occurring at different sizes and frequencies under various levels of protection in the area, and (c) the effects of those fires on the hydrologic potential values.

The authors have used the results of several previous studies to develop a procedure for measuring the expected net effects of wildfires on hydrologic values located in the area protected by the California Department of Forestry.

HYDROLOGIC OUTPUT PARAMETERS

The earlier studies found that hydrologic values may be indexed by measuring output parameters of floods, sedimentation, and water supply:

Floods: Annual maximum daily streamflow; 10-year maximum daily flow; and flood overflow rate.

Sedimentation: Deposition in reservoirs, channels, and overflow areas; suspended sediment discharge; and sedimentation from roads.

¹Presented at the Symposium on Dynamics and Management of Mediterranean-type Ecosystems, June 22-26, 1981, San Diego, California.

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Abstract: Expected effects of wildland fires on hydrologic values have been indexed by 11 hydrologic parameters of floods, sedimentation and water supply. Coefficients and watershed attributes from 10 multiple-regression models are used to distribute measured hydrologic parameters throughout each watershed. Other coefficients are used with present fire condition and fire frequency to estimate changes in the hydrologic parameters for four fire conditions: unburned, 1 percent average annual burn, after a 100 percent burn, and after a burn of 10,000 acres (3900 ha). Application is illustrated for north coastal, Sierra Nevada, and southern California watersheds.

Water Supply: Mean annual streamflow; median annual minimum daily flow; 10-year annual minimum daily flow; average sediment concentration in streamflow; and turbid streamflow in days per year and its effects on water supply, fishability, and aquatic habitat and fish production.

WATERSHED ATTRIBUTES

Optimum management of the parameters of floods, sedimentation, and water supply with and among groups of watersheds requires evaluation of the contribution of the sources and causes of differences in those output parameters. The earlier hydrologic studies identified the attributes of individual watersheds that can be measured to explain differences in hydrologic output parameters between watersheds.

The use of measured outputs from many watersheds with diverse attributes makes it possible to evaluate the independent effect of an attribute on the hydrologic output parameters from watersheds. Different values of attributes produce different amounts of a hydrologic output parameter. Therefore different parts of watersheds with those differences in attributes may be reasoned to also contribute those relative differences in the amounts of the output parameters.

Watershed attributes and the distribution of attributes within watersheds were taken from aerial photographs and from maps of precipitation, topography, geologic rock types, landslide potential, and land use. They were taken also from the results of studies of the relation of specific attributes--such as rain/snow frequency, soil texture, and density of sediments--to mapped and photo-interpreted attributes.

Principal component and multiple regression analysis were the statistical tools used to test independence among the attributes to be evaluated and to evaluate the quantitative relation of each attribute (or variables expressing an attribute) to measured hydrologic output parameters. As many as 29 variables were used in a single evaluation. Several variables might be used for a single attribute. For example, 9 variables represented the geology attribute. As few as 23 and as many

as 95 watersheds were used to make the evaluations in the different studies. The principal attributes and their variables used in evaluating watershed outputs or in distributing hydrologic output parameters to their sources within watersheds were:

Meteorological Attributes: Mean annual precipitation; rain/snow frequency; and storm and pre-storm precipitation.

Soil-Geologic Attributes: Geological rock types; landslide potential; and soil texture.

Topographic Attributes: Area-elevation; slope of tributary streams; shape of watershed; and channel morphology.

Hydrologic Attributes: Daily streamflow; annual peak flow; sediment concentration; and periodic reservoir deposition.

Land-Use and Condition Attributes: Fire frequency; vegetation types; timber harvest; and roading.

Specific variables and units used in the analyses are given in Table 1.

The distribution of attributes in a watershed was estimated from measured hydrologic output parameters. The contribution of each area of the watershed to each hydrologic output parameter was estimated through the use of one or more of 10 multiple regression models developed in earlier studies. The models were applied also to watersheds for which no hydrologic output parameters had been measured. This application was made by relating the watershed to an adjacent watershed which had been studied and which had other known attributes similar to those of the unmeasured watershed.

FOREST FIRE ATTRIBUTES

Several attributes of forest fires are used in this procedure to index the effects of wildfires on hydrologic output parameters from watersheds. The attribute selected for a given watershed depends on the available data and how a particular hydrologic output parameter might be affected by wildfire. Thus, the procedure for northern California watersheds uses the total area of burns in the 10 years prior to a measurement in evaluating the effects of fire on suspended sediment discharge and on all streamflow parameters. That procedure also uses fire "effectiveness," depleted year by year for 26 years, for reservoir deposition. The procedure for southern California watersheds uses the effect of fire on cover density and the recovery of cover density to index the effects of fires on flood peaks and reservoir sedimentation (Table 1).

Table 1--Variables and fire effects used in analyses.

Symbol	b ¹	Description and unit
MAQ	9	Mean ann. streamflow (in. dep./yr)
DQ	13	Median max. ann. daily Q (cfs/m ²)
QTEN	22	Max. daily Q in 10 yrs. (cfs/mi ²)
QM	48	Median ann. min. daily Q (cfs/mi ²)
QM10	39	10-yr. min. daily Q (cfs/mi ²)
QP	10	Peak Q of storm or yr. (cfs/mi ²)
FL	38	Flood channel overflow (cfs/mi ²)
SS	171	Suspended sediment discharge (T/mi ² /yr.)
SC	149	Average suspended sediment conc. (mg/l)
TD		Turbid days with SC in a class (pct)
RD	49	Reservoir deposition, No. Calif. (m ³ /h/yr.)
eD	17	Reservoir deposition, So. Calif. (AF/mi ² /ry)
q		Ann. peak streamflow (cfs/mi ²)
Q1		Isoline of MAQ (in./yr.)
DQ1		Isoline of DQ (cfs/mi ²)
Q10		Isoline of QTEN (cfs/mi ²)
QM1		Isoline of QM (cfs/mi ²)
QM101		Isoline of QM10 (cfs/mi)
MAP		Mean ann. precipitation (in./yr.)
P ₂₄		Max. 24-hr. precipitation (in.)
aP		Antecedent precipitation during 21 days before a storm (inches)
RRA		Snow area, frequency of snow vs. rainstorms (pct.)
EL		Elevation (feet)
LAT		Latitude north (degrees)
AVLS		Landslide potential, per Radbruch & Crowther (class)
AVLS		Landslide potential adjusted for Q1 (class)
C(t)		Vegetation cover density (pct.)
t		Time since area burned (years)
AVBR		Average ann. burned area (pct.)
UNBR		Unburned
10M		10,000 acre fire in watershed 2
Ach		Area of main channel (acres/mi)
k		Any constant

¹"b" is the percentage increase of the hydrologic output parameter for each one percent of average annual burn; the "b" value for TD, q, and FP depend on individual watershed attributes.

The general model used to adjust each hydrologic parameter for different fire conditions is that the present measured value of the hydrologic parameter is multiplied by the regression coefficient for fire times the change in the parameter because of fire. The hydrologic output for present fire conditions is adjusted to 4 fire conditions or effects: (1) unburned condition; (2) changes induced by an average annual burn of one percent of the watershed; (3) changes induced by a 10,000-acre burn within the watershed (both the first year's effect after the fire and the average annual effect over 10 years following the fire); and (4) changes induced by a conflagration that includes the entire watershed (again, both the

first year's effect after the fire and the average annual effect over 10 years following the fire).

Changes in the hydrologic output parameters may then be translated into potential economic and social effects. These effects are related to local and regional demands for water supply, utility of reservoirs, fish production and fishability, transportation systems, and to human occupancy, property, and land-use within the 2- to 100-year flood plains. These economic and/or social indexes then provide one basis for planning and evaluating alternative systems of wildland fire protection.

ECONOMIC MODEL

The general form of the economic equation is: The change in watershed value because of fire is equal to the normal state in a particular hydrologic output parameter times the change in that parameter because of fire, times the change in value (in dollars) per unit of that parameter. To determine the total change in watershed values because of fire, these dollar values are summed for all 11 hydrologic output parameters.

The general model represents our present knowledge. It is not complete. It does not include, for example, measures in the changes of soil productivity or of in-stream chemistry. There are simply no good or easy ways at present to measure those changes due to fire. Further research will lead to better models in the future.

PROCEDURE FOR MEASURING FIRE EFFECTS ON HYDROLOGIC OUTPUT PARAMETERS

Three steps are involved for each of the 11 hydrologic output parameters: (1) estimating whole-watershed outputs; (2) determining the distribution of partial watershed contributions; and (3) estimating the change in each hydrologic output parameter with fire.

These steps will be illustrated in detail for only one of the 11 parameters; details of calculations for other parameters of streamflow, flood flows, sedimentation, and water quality are available upon request.³

Flood and sedimentation estimates for southern California watersheds will be described later.

Estimating Streamflow Parameters for Watersheds

Average annual streamflow, median daily maximum flow, 10-year maximum daily flow, median

³Estimating hydrologic values for planning wildland fire protection. Henry W. Anderson and Clinton B. Phillips, Calif. Dept. of Forestry, 1416 Ninth St., Sacramento, California 95814. 40 p., illus. File Report, 1981.

daily minimum flow, and 10-year minimum daily flow may be taken directly from published tabulations of the U.S. Geological Survey (1971). Flood overflow is taken as the 10-year maximum flow minus the median annual daily maximum flow.

Distributing Streamflow Parameters Within Watersheds

Mean annual streamflow (MAQ) by itself is an important hydrologic output parameter. It is also an important attribute for evaluating and explaining sedimentation, landslide potential, and water quality. As a hydrologic output parameter, mean annual streamflow explains the filling of reservoirs having holdover (more than one year) capacity. As an attribute of watersheds, mean annual streamflow is an important variable of the spatial variation of the meteorological potential. Therefore, the distribution of mean annual streamflow within a watershed is evaluated first.

To make this distribution, we use Equation (1) from Table 2 (Anderson 1975). A first approximation of k in the equation is calculated by taking the distribution of mean annual precipitation (MAP) from the state isohyetal map (U.S. Geological Survey 1969) together with the measured streamflow and the relation of streamflow to precipitation.

Table 2--Equations used in analysis.

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- (1) $MAQ = k + 0.442 MAP + .004318 MAP^2 - 0.128 RRA$
 - (2) $RRA = 100 \{1 - [EL - 250 (LAT - 46)^2 / (LAT \times 10^6)]\}$
 - (3) $\Delta MAQ / \Delta AVBR = \text{antilog} (0.0378 \Delta ABR)$
 - (4) $DQ = k + 0.627 MAP + .00592 MAP^2 + 0.91 RRA$
 - (5) $QTEN = k + 1.325 MAP + 0.013 MAP^2 + 0.078 RRA$
 - (6) $\log QM = k + 0.774 \log MAP - .0081 RRA + 0.620 \log EL$
 - (7) $\log QM10 = k + 0.5061 \log MAP + .0061 RRA + 0.4127 \log EL$
 - (8) $\log SS = k + 0.335 \log Q1 + 0.214 AVLS$
 - (9) $AVLS = AVLS + 1.68 \log (Q1/MAQ)$
 - (10) $\log RD = k + 0.1397 \log MAP + .0255 \log MAP^2 - .0128 SA$
 - (11) $SS = RD ((\text{silt} + \text{clay} - 32) \times 0.045)$
 - (12) $SC = 13.79 (SS/Q1)$
 - (13) $C(t) = C_{\text{Min}} + C_{\text{Max}} (1 - e^{-kt})$
 - (14) $\log FP = 1.293 + 1.082 \log \text{area} + 1.870 \log P_{24} + 0.474 \log aP - 0.825 \log C$
 - (15) $\log eD = 1.041 + 0.866 \log FP - 1.236 \log C + 0.371 \log Ach$
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Isolines of mean annual streamflow for selected values (Q1) are drawn parallel to MAP lines by substituting values of Q1 for MAQ in Equation (1) and using the computed value of k.

Mean annual streamflow must be adjusted for different contributions of rain and snow storms (RRA) in those areas where both types of precipitation occur (Anderson 1975). The percent of rain-versus-snow storms is given in Anderson and Wallis (1963). It may be approximated by our Equation 2, using latitude (LAT) in degrees North and elevation (EL) in feet.

Measuring Fire Effects on Mean Annual Streamflow

The primary effect of fire on mean annual streamflow is on the availability of water for all uses. If MAQ is increased, there probably is an increased economic value. But if the increased MAQ occurs mostly in a relatively short period of time, and is accompanied by an increase in suspended sediment then the effect could be a negative economic value.

To evaluate the effects of mean annual streamflow, it is necessary to measure the average annual percent of an area burned (AVBR) associated with the particular mean annual streamflow. That measurement is obtained from historical fire records of the appropriate fire protection agencies. The change in mean annual streamflow because of the effects of fire (MAQAVBR) is given by Equation 3, Table 2 (Anderson 1975). Other changes in mean annual streamflow are given by the following formulas (terms are defined in Table 1):

For the unburned condition:

$$\text{MAQUNBR} = \frac{\text{MAQAVBR}}{\text{antilog}(0.0378 \times \text{AVBR})}$$

For the 1 percent annual burn:

$$\begin{aligned} \text{MAQ1pct.} &= \text{MAQUNBR} \times \text{antilog}(0.0378 \times 1) \\ &= \text{MAQUNBR} \times 1.09 \end{aligned}$$

For the 100 percent burn, 1 year after the fire (MAQ 100 pct.): No positive estimate of this parameter can be made because the effects of a fire are dependent on the soil moisture relations, precipitation, and recovery of vegetation. Study of the Tillamook Burn in Oregon (Anderson 1976(b) showed a 16-year increase of 11 percent in mean annual streamflow. Using this figure as an estimate, we get a first year increase in MAQ of 21 percent:

$$\begin{aligned} \text{MAQ 100 pct.} &= \text{MAQUNBR} \times 100 + (11 \times 2 - 1) / 100 \\ &= \text{MAQUNBR} \times 1.21 \end{aligned}$$

For the 10,000-acre burn, 1 year after the fire (MAQ10MAC): We calculate the average effect over 10 years from the ratio of the 10,000 acres burned to the area of the whole watershed times the 21 percent obtained for MAQ100pct. Multiplying this effect by 2 gives the first-year effect.

$$\begin{aligned} \text{MAQ10MAC} &= \text{MAQUNBR} (10000 \times 1.21) + \\ &\quad (\text{WPUA} - 10000) / \text{WPUA} \end{aligned}$$

Median maximum annual daily streamflow (DQ) is distributed on the basis of the distribution of MAP, using the relation of DQ to MAP and RRA in Equation 4, Table 2 (Anderson 1975) and the k value for that watershed.

Ten-year maximum daily streamflow (QTEN) is distributed on the basis of the distribution of MAP, using the relation of QTEN to MAP and RRA from the regression results of Anderson (1975) in Equation 5, Table 2, and the k value for that watershed.

The flood overflow (FL) contribution of watershed parts is taken as the difference between the Q10 isolines and the median daily flow isolines.

For watershed areas without measured streamflow, flow from a similar watershed area may be used to make estimates of Q10 and DQ. The 10-year flow is particularly sensitive to the contrast of basalt-versus-granite geologic rock types (Anderson 1975).

The annual (median) daily flow (QM), read from tabulations, may be distributed to get an estimate of the "relative contribution of watershed parts" by relation to the distribution of mean annual precipitation (MAP), rain-versus-snow frequency (RRA), and mean elevation in feet (EL), from Equation 6, Table 2 (Anderson 1975), and the k value for that watershed.

10-year minimum daily streamflow (QM10) is an indicator of drought and may have special interest in some areas. To the extent that forest fires might help to mitigate that drought problem by causing the release of additional water, fires might have a beneficial effect. The contribution of parts of watersheds to QM10 may be estimated from Equation 7, Table 2, and the k value for that watershed.

Distributing Other Streamflow Parameters Within Watersheds

The other selected streamflow parameters--maximum annual daily streamflow (DQ), 10-year maximum daily streamflow (QTEN), flood overflow (FL), minimum annual daily streamflow (QM), and 10-year minimum daily streamflow (QM10)--are distributed by methods similar to that used for MAQ, above, by applying Equations 4 to 7, Table 2.

Measuring Fire Effects on Other Streamflow Parameters

Fire effects on the other streamflow parameters are calculated by methods similar to that used for fire effects on MAQ, previously outlined, but using the appropriate value of "b", the one percent effect (see the footnote for Table 1). See footnote 3 on how to obtain further details.

Estimating Sedimentation Parameters for Watersheds

Suspended sediment discharge and deposition of sediment in reservoirs provide the quantitative base for evaluation of sedimentation. Suspended sediment parameters are estimated from published daily sediment concentration measurements, streamflow frequency, and the relation of sediment concentration to streamflow. This procedure gives directly (1) the average sediment concentration, (2) the product of sediment concentration and average annual streamflow which is suspended sediment discharge, and (3) the frequency both of percent of turbid days (TD) and percent of volumes of water by sediment concentration classes. These variables are related to water quality (Anderson 1979, Table 1). Reservoir depositions are taken directly from published measurements. Summaries have been published by the Soil Conservation Service (1965) and periodically by other agencies such as flood control districts, state and federal experiment stations, and by interagency river basin committees.

Distributing Suspended Sediment Parameters Within Watersheds

As a basis for sediment management, the sources of sediment parameters provide the best basis for allocating resources and providing fire protection. Measurements of sediment discharge (SS), sediment concentration (SC), and turbid days (TD) from a watershed may be distributed based on the distribution of mean annual streamflow (Q1), the landslide potential (AVLS) (Radbruch and Crowther 1973), and the relation of suspended sediment discharge to these two variables obtained from multiple regression analysis, Equations 8 and 9, Table 2 (Anderson 1979). Again a separate k value is computed for each watershed.

For a watershed for which no suspended sediment discharge has been measured previously, suspended sediment discharge and the distribution of SS classes may be estimated from a nearby "known" watershed. The measurements of the "known" watershed are adjusted to account for differences in the attributes of the "known" and "unknown" watersheds, using appropriate coefficients for road effects (Anderson 1975) and other variables from Anderson (1979).

If suspended sediment (SS) is the desired parameter, but only reservoir deposition (RD) has been measured in a watershed, SS may be approximated by using the estimated silt and clay content of the soil (Anderson 1954). Substituting silt and clay in Equation 11, Table 2, gives a correction factor for RD. Silt plus clay may be estimated for geologic rock types, elevation, and latitude from relations developed by Wallis and Willen (1963) or from soil surveys where soil series and types have been established.

Measuring Fire Effects on Sediment Parameters

The effects of fire on sediment discharge, sediment concentration, reservoir deposition, and turbid days have economic impacts in 3 areas: water quality, water use, and property damage. Adjustment of sediment parameters may be made in a manner similar to that for streamflow, using the "b" value from Table 1.

The effect of the 4 fire conditions on sediment-induced losses of water suitable for domestic or other uses or for aquatic habitat, if relatable to turbid days (TD) or turbid volumes (TV), may be estimated from the changes brought about by fire on suspended sediment concentration and streamflow frequency. The new streamflow and new sediment concentration are substituted in the frequency table (Anderson 1979, Table 1). That step gives the difference in the volumes of suitable water provided by the various fire conditions.

Distribution of Reservoir Deposition to Parts of Watershed

Rates of reservoir deposition contributed by parts of watersheds may be obtained by analogy to suspended sediment discharge, using Equations 10 and 11, Table 2. Fire effects on reservoir deposition may be estimated from the "b" value, the one percent burn effect, from Table 1.

WATERSHED VALUES AFFECTED BY FIRE IN SOUTHERN CALIFORNIA

The brushland watersheds of southern California and south coastal California require a special evaluation of watershed values affected by fire. In those areas a system of models can be used that is simpler than those used for northern California.

Several characteristics of the system make it possible to keep its calculation quite simple: (a) flood peaks (QP) and sedimentation (eD) from the watersheds are related to the vegetation cover density (C) on the watersheds; (b) the cover density for each vegetative and geologic type is related to the age classes (t) of the vegetation which in turn are related to forest fires; and (c) two rather simple precipitation parameters (P₂₄ and aP) and past records of streamflow give a basis for correcting past frequencies and for estimating expected future flood events and, hence, flood and sedimentation damages under different fire protection programs.

The cover density (C) varies with time (t) from the fire as shown in Equation 13, Table 2, with the coefficients Min, Max, and k varying among 13 cover types and three geologic types (Anderson and Trobitz 1949).

On the basis of Equation 14, Table 2, a second model (Anderson 1949) relates reservoir deposition to the size of floods, cover density, and channel conditions (Equation 15, Table 2). For reservoir deposition in T/mi²/yr., the constant is 4.342 instead of 1.041 (assuming 2,000 tons per acre-foot).

Fire Effects on Sediment Discharge and Flood Peaks

Fire effects on sediment discharge and flood peaks have been calculated for many southern California and south coastal California watersheds. Data for 41 watersheds are summarized in Anderson (1949). Data for other watersheds are given in USDA Flood Control Reports (1949-1952). The "b" values (Table 1) for one percent annual burn apply to Big Dalton watershed only.

DISCUSSION

Application of the above procedures has been illustrated for individual tributaries of the Russian River watershed (1700 mi², 4400 km²) in the north coast, the Bear River watershed (150 mi², 389 km²) in the Sierra Nevada, and the Big Dalton (4.4 mi², 11 km²) watershed in southern California.⁴ Maps showing the distribution of each streamflow and sediment parameter within the two northern California watersheds have been prepared; tables give measures of the hydrologic parameters for watershed tributaries and fire planning units for various burn conditions. With the Russian River watershed, for example, mean annual streamflow varied for 15 to 50 inches (380 to 1270 mm), mean annual suspended sediment discharge varied from 100 to 9400 tons/mi² (35 to 3300 tonnes/km²), and average suspended concentration varied from 90 to 2600 mg/liter.

Further refinement in the maps may be made by application of the regression coefficients for differences in local slope, geologic fault areas, soil texture and erodibility, and land use.

We must ask, are the hydrologic effects of a succession of burns different than the effects of a single burn? Two studies have indicated cumulative effects or non-recovery following burns: the effects of "old fires" on sediment discharge from the 1938 flood in southern California (Anderson and Trobitz 1949) and the effects of high elevation brushfields resulting from repeated burning attributed to early shepherders (Anderson 1974).

The adjustment of hydrologic outputs for expected fire frequency under various levels and practices of fire protection gives a basis for allocating protection funds for maximum economic and social benefits.

⁴Henry W. Anderson and Clinton B. Phillips. op. cit.

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