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Reanalysis of Past Research on Effects of Fire on Wildland Hydrology

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In spite of ever-increasing efforts and expenditures directed toward forest fire protection, it is expected that fire will continue to be a primary consideration in the future management of our wildlands. In order to regulate our efforts, it is important that we be able to estimate the potential social and economic losses which might be incurred under varying intensities of protection. In the past, losses of certain watershed values have sometimes been the most dramatic consequence of wildfire. But how do we quantify these potential losses? Is the effect on the hydrology of our wildlands caused by burning enough understood?

Undisturbed forest and range cover normally afford adequate protection for the water resource. When the watershed cover is altered by fire, a reduction in this protective influence is reflected by the change brought about in several basic hydrologic processes. The magnitude of this response is related to (1) the degree to which the normal hydrology of the soil and vegetative and litter cover has been jeopardized, (2) the physiography, and (3) the meteorologic conditions attending post fire runoff events.

A significant volume of published information generally concerned with the effects of fire on infiltration, runoff, and erosion from forest land already exists. The bulk of these publications originates in the southwestern portion of the country where these problems have been of major economic importance for many years. It is apparent that fire is most influential in altering the hydrology of the soil surface. Fire reduces the ground cover and exposes the surface soil to the compaction of direct raindrop impact. This subsequently leads to a reduction in infiltration (Arend, 1941; Heyward, 1939; and Beaton, 1959).

Associated with this decrease in infiltration capacity has been an increase in total runoff and erosion (Sampson, 1944: Meginnes, 1935; and Copley *et al.,* 1944). Many investigators, using a limited number of observations, have reported significant increases in watershed peak runoff and sediment discharge (Hoyt and Troxell, 1934; Sampson, 1944; and Sinclair and Hamilton, 1955). These general responses have been accepted as some of the more notable consequences of burning our wildlands.

However, the complexities of the hydrologic processes involved have also led to frequent contradictions. For example, on certain soils infiltration has been found to increase or remain unchanged following a fire (Scott and Burgy, 1956; Burns, 1952, and Hodgkins, 1957). Similarly, following some early runoff plot studies conducted in California, F. J. Veihmeyer concluded that neither runoff nor erosion had been accelerated by burning (In Adams, *et al.* 1947). Colman (1951) pointed out that floods and heavy erosion do not always follow fire.

There have been geographic variations in the importance placed on the fire-hydrology response. Although fire has long been part of the natural history of the eastern hardwood forests, little research effort has been extended to problems related to the hydrologic changes and damages associated with burning in this broad region—possibly because, hydrologically, they are of little importance. California, on the other hand, has long led the way in fire-hydrology research, particularly on chaparral and sparsely-timbered rangelands. The emphasis is not solely on the potential presence or absence of fire on the forests and rangelands of a region but on the degree to which the normal vegetative, physiographic, edaphic, and climatic complex responds hydrologically.

How are we to interpret the variable and frequently conflicting reports? Colman (1953, p. 277) states "...Only when the characteristics of rainfall, soil, slope and vegetation in particular places are taken into account in burning studies will we know the conditions under which the damaging hydrologic effects of fire are severe, light, or inconsequential." Thus, the magnitude of runoff and erosion change depends on the quantities involved. These in turn vary from place to place in response to local conditions. Different soils are subject to different volumes of runoff and erosion, both before and after alteration by any agent such as fire. The hydrology of rugged terrain is different from that of relatively level topography. In some regions vegetation recovery is rapid following fire, and any deviation from the normal hydrologic pattern is often short-lived. Where rains are prevailingly gentle, burning will not ordinarily be followed by severe surface washing. On the other hand, where intense rains are frequent, burning often leads to drastic increases in overland flow and erosion. Often the timing of the fire-rainfall sequence is of primary importance. In addition, in some regions or during certain seasons fires are rarely hot enough to consume the protective forest floor. Therefore the direction, magnitude, and duration of the hydrologic response to fire is a function of a number of interacting factors.

As an initial step toward strengthening our understanding of fire-hydrology response on forest and rangelands, it was felt that a careful examination of past research would be appropriate. A sufficient volume of data on a large number of variables was already available from the literature so that a thorough re-examination of existing research results seemed a logical first step. Toward this end, a careful tabulation was made of pertinent quantitative and qualitative information from a majority of the available publications. Where necessary, data were converted to uniform units for ease of comparison and analysis.

Past research on the general subject has been carried out along three lines: (1) infiltration studies, (2) runoff plot studies, and (3) watershed studies. The bulk of the work has been concentrated in the first two areas. Few paired or controlled watershed studies have been conducted specifically to determine the effects of wildfire on the hydrology of an entire drainage. To this date, none have yielded results in the vast eastern hardwood region. Documentation of the variables involved was generally more complete in the infiltration and runoff plot investigations.

Within the qualitative and quantitative limits imposed by the extracted data, an attempt was made to model the hydrologic response to fire through a series of multiple regression analyses. It was hoped that the major significant influencing variables and their relative importance could thereby be determined. A secondary purpose for the investigation was to delineate obvious gaps in our research and point up promising areas for more intense future study.

To screen the mass of data covering a variety of dependent and independent variables, a preliminary graphical analysis was carried out. Single independent variables were plotted against each of the various dependent variables. Dependent variables were selected functions of the change in normal hydrology brought about by fire, i.e. runoff increase, infiltration increase or decrease, erosion, etc. This graphical presentation served to (1) point out variables for which insufficient data were available for inclusion in the mathematical analysis and (2) point out some of the more easily established relationships. The absence of a visible correlation between a pair of variables did not necessarily eliminate the independent variable data from the multivariate mathematical analysis.

Statistical analyses were conducted on the data from the three study types. Multiple regressions were computed for all combinations of one or more independent variables against the various hydrologic change functions. In all, 2,721 separate equations were generated. Many of these were statistically significant at the 5 or 1 percent level of probability; only a few selected ones will be presented below. The variables included in the models are listed in Table 1.

To obtain and present the most complete mathematical expression for each of the several hydrologic response functions the "maximum equation" significant at the 1 percent level of probability was determined. This equation in all cases contained only those variables which were instrumental in increasing the correlation and which at the same time appreciably reduced the statistical variability. The actual make-up of the equations, of course, depended on the extent and character of the variables found in the data source. This point is important from the standpoint of limiting the interpretation and general transposition of the models . Similarly, representation by a data source in an equation depends on

TABLE 1. SYMBOLS FOR THE REGRESSION MODELS

Symbol	Explanation
I_r	ratio: burned soil infiltration/ unburned soil infiltration
I_u	unburned soil infiltration (inches/hour)
N	number of annual burns
T_c	soil texture (average per cent clay)
T	soil texture (numerical rankings-see text and Table 2)
$\log R_r$	logarithm of ratio: total annual burned plot runoff/total annual unburned plot runoff
R_u	total unburned plot runoff
S	plot per cent slope
P_a	total annual precipitation (inches)
P_s	total storm precipitation (inches)
E_r	ratio: annual unburned plot erosion/ annual burned plot erosion
E_u	annual unburned plot erosion (lbs./acre)
RP_b	peak discharge from burned watershed (csm)
RP_u	peak discharge from unburned watershed (csm)
A_t	total watershed area (acres)
A_b	per cent of total watershed area burned

TABLE 2. SOIL TEXTURE VARIABLE

Textured Class	Percent Clay (Tc)	Numerical Values (T)
Clay	70	1
Clay loam	34	2
Silty clay loam	34	3
Sandy clay loam	28	4
Silt loam	20	5
Fine sandy loam	15	6
Sandy loam	10	7
Sand	5	8

the presence or absence of the particular variables included in the original study. Therefore, although many more data sources were screened, relatively few were used in the preparation of the models.

Infiltration Studies

Through the years infiltration has been measured using a number of different techniques and instruments. Rates obtained in one study are rarely directly comparable to those obtained under different experimental conditions in another.

Direct comparisons between infiltration rates obtained from different studies, possibly utilizing a number of experimental approaches, have been attempted by computing ratios of infiltration rates in inches per hour on burned soil. Although the problem of differences in instrumentation was not totally avoided through the use of ratios, an estimate of relative response can be obtained using this technique. This relative response of infiltration to fire served as the dependent variable in all infiltration study models.

The following expression was computed from two data sources. Data and reference sources for all models are listed in Table 3. The interpretation of this and following mathematical expressions must be limited by the range of available data used in the calculations. These limitations have been noted where appropriate.

$$I_r = 1.644 - 0.004I_u - 0.015N - 0.052T_c \qquad \text{(equation 1)}$$

The preceding infiltration equation had an R^2 of .858 and a standard error of estimate of ±0.134.

A reduction in I_r represents a reduction in the infiltration rate following fire. As I_u, unburned infiltration, N, number of annual burns, and T_c, soil texture - per cent clay increase, this reduction in the infiltration capacity also increases.

The variable T_c corresponds to a soil textural measure. Soil texture was probably the most universally reported soil feature. For ease of quantification, textural groups were assigned values according to the average percentage of clay for each broad class as seen in Table 2 (U.S.D.A., 1951). Admittedly, the values assigned to specific reported soils may be grossly in error. The actual percentage of clay varies widely for each soil textural classification. However, considering the objectives of the investigation and the absence of more precise soils information, it was felt that the relative influence of the various soil textural groups on the fire response could most acceptably be expressed in this manner.

Thus, according to the model, the influence of fire would be more striking on the coarser-textured soils. However data were available only from studies conducted on loamy to more coarse-textured sandy soils. Since these lighter soils have higher infiltration capacity, it seems logical that they would offer greater opportunity for change following a treatment such as fire.

The infiltration rate of the control or unburned soils, I_u, is an expression of the combined influence of a number of variables including soil texture, structure, porosity, litter cover, etc. The greater the inherent capacity of an undisturbed soil to infiltrate water, the greater the change (a reduction according to the model) induced by the introduction of fire.

As a site is burned annually for a number of years (N) the effect on infiltration increases. The available data did not indicate whether there was a point in terms of the number of annual burns whereafter this influence becomes stabilized.

As was also true of the other two study types, additional variables were included in several other significant mathematical expressions of the fire - infiltra-

TABLE 3. REFERENCES AND DATA* USED IN REGRESSION MODELS

		Variables				
Equation	References	Infiltration unburned I_u (inches/hour)	Number of annual burns N	Soil Texture T_c % Clay	Infiltration ratio I_r burned/unburned	Region
1	Arend, 1941	1.92	1	20	0.6	Eastern (hardwoods)
		1.76	1	20	0.5	
		1.67	1	20	0.8	
		2.49	1	20	0.4	
		1.71	1	20	0.5	
		2.04	1	20	0.7	
		3.29	1	20	0.7	
1	Burns, 1952	96.50	1	5	1.1	Northeast (hardwood-pine)
		96.50	2	5	1.0	
		96.50	3	5	0.9	
		96.50	4	5	1.1	
		96.50	5	5	1.0	
		96.50	6	5	0.9	
		96.50	15	5	0.7	
		73.80	1	5	0.8	
		73.80	2	5	1.1	
		73.80	3	5	1.1	
		73.80	3	5	1.2	
		73.80	4	5	1.2	
		73.80	6	5	1.1	
		73.80	1	5	1.0	

Table 3 (continued)

		Variables					
Equation	References	Annual precipitation P_a (inches)	Runoff unburned plot R_u inches	Slope S percent	Soil Texture rank** T	Runoff ratio† R_r burned/ unburned	Region
2	Daniel, et. al., 1943	29.77	.04	5.2	6	110.0	Eastern (hardwoods)
		37.73	.06	5.2	6	55.0	
		31.85	.07	5.2	6	30.7	
		34.96	.15	5.2	6	14.9	
		32.80	.02	5.2	6	105.0	
		25.21	.01	5.2	6	43.0	
		23.12	.01	5.2	6	2.0	
2	Meginnes, 1935	60.44	1.03	10.0	5	10.5	Eastern (hardwoods)
2	Pope, et. al., 1946	45.62	.73	12.5	6	2.1	Eastern (hardwoods)
		46.15	.09	12.5	6	12.7	
		34.18	.08	12.5	6	9.5	
		48.88	.15	12.5	6	8.9	
		33.97	.10	12.5	6	7.8	
		38.75	.03	12.5	6	23.3	
		32.15	.03	12.5	6	35.0	
		52.15	.02	12.5	6	78.5	
		40.95	.14	12.5	6	29.2	
2	Rowe, ____	40.51	.02	32.0	4	54.5	California
		40.51	.02	32.0	4	9.5	
		24.42	.01	32.0	4	14.7	
		24.42	.01	32.0	4	13.3	
		19.67	.01	32.0	4	13.7	
		19.67	.01	32.0	4	156.2	

Table 3 (continued)

		Variables					
Equation	References	Annual precipitation P_a inches	Erosion unburned E_u lbs./acre	Slope S percent	Soil Texture rank** R	Erosion ratio E_r unburned/burned	Region
2 (continued)	Rowe, ________	41.24	.02	32.0	4	12.7	
		41.24	.02	32.0	4	352.1	
		37.92	.04	32.0	4	4.7	
		37.92	.04	32.0	4	127.6	
		41.09	.01	32.0	4	183.0	
		41.09	.01	32.0	4	680.4	
		60.77	.03	32.0	4	728.3	
3	Daniel, et. al., 1943	37.73	7.80	5.2	6	1.7	Eastern (hardwoods)
		31.85	4.00	5.2	6	.5	
		34.96	1.60	5.2	6	1.2	
		32.80	3.70	5.2	6	1.2	
		21.52	.40	5.2	6	.3	
		30.57	.20	5.2	6	.9	
3	Meginnes, 1935	60.44	684.40	10.0	5	.1	Eastern (hardwoods)
	Pope, et. al., 1946	45.62	60.00	12.5	6	.4	Eastern (hardwoods)
		34.81	400.00	12.5	6	2.7	
		48.88	140.00	12.5	6	.1	
		33.97	160.00	12.5	6	.1	
		38.75	20.00	12.5	6	.1	
		32.15	10.00	12.5	6	.1	
		52.15	10.00	12.5	6	.1	
		40.95	100.00	12.5	6	.1	

Table 3 (continued)

Equations 4 and 5	References	Variables						
		Storm Precipitation P_s inches	Runoff Peak unburned RP_u csm	Area burned A_b percent of total area	Total area A_t acres	Soil Texture T_c Percent clay	Runoff Peak burned RP_b csm	Region
	U.S. Forest Service (Staff, San Dimas Exp. Forest) 1954	7.27	.98	26.0	1370.8	5	55.01	California (chaparral)
		7.27	.67	3.0	1370.8	5	11.84	
		5.61	.98	26.0	1370.8	5	26.47	
		5.61	.67	3.0	1370.8	5	19.66	
		2.35	3.54	26.0	1370.8	5	12.61	
		2.35	2.48	3.0	1370.8	5	5.09	
		3.59	3.54	26.0	1370.8	5	8.74	
		3.59	2.48	3.0	1370.8	5	3.06	
	Rich, 1962	3.41	16.20	19.0	318.2	34	155.60	Southwest (pine-chaparral)
		1.20	3.20	19.0	318.2	34	38.60	
		1.33	6.20	19.0	318.2	34	32.40	
		1.50	2.80	19.0	318.2	34	42.60	

*Original data converted to units to conform to those used in this analysis where necessary.

**See Table 2.

†Logarithmic values used in equations.

tion response. In several equations, for example, the total residual litter depth following fire was found to be important. However, because of the paucity of data or greater statistical variation, these and other models will not be presented here.

Runoff Plot Studies

A proportionally greater amount of data covering a broader range of variables was available from the runoff plot studies. This afforded a greater opportunity to test the effect of many variables, singly and in combination, on the fire-hydrology response.

The effect of fire in all cases was determined to be the difference in total annual runoff in inches and erosion in pounds per acre between burned and unburned paired plots. Although some studies reported on the response to single storm events, insufficient data were available for analysis. The following runoff equations were generated from data derived, for the most part, from studies carried out in the eastern hardwood region. Again, the measure of the effect of burning was computed to be the ratio of treated to untreated plot runoff.

$$\log R_r = -2.729 + 0.035P_a - 4.138R_u - 0.157S + 0.438T_c \qquad \text{(equation 2)}$$

where $\log R_r$ is the logarithmic function of the dependent variable, the ratio of burned to unburned runoff. In most cases, the multiple regression was computed for both the logarithmic and nonlogarithmic response measure. In this case, the R^2 (.902) and the standard error of the estimate ($\pm$ logarithm 0.67529) were superior for the logarithmic function.

According to the above relationship, as the annual precipitation (P_a) increases, the relative differences in runoff between the burned and unburned plots also increases. The response following fire is more significant on the heavier soils as reflected by the textural variable (T_c). Removal of the litter cover by fire is apparently more critical on soils with inherently slow infiltration capacity.

It appears as though the remaining variables, the unburned plot runoff (R_u), and the per cent slope of the plot (S) have an inverse effect. That is, as unburned plot runoff and slope per cent increases in magnitude, the response of the plot to fire relative to the unburned control decreases. The capacity of a site to detour the annual precipitation (P_a) from infiltration into the soil to overland flow (R_u) is influenced, in part, by slope. As the magnitude of this plot feature increases, the potential for increasing the proportion of precipitation diverted to overland flow through treatment becomes less. Regardless of this relative reduction, fire increases total annual runoff.

The range in data for the slope factor (S) was rather limited. Whether or not this relationship will hold will have to be established through more detailed study.

Fewer runoff plot studies included data on effects of fire on erosion from a forest site. In general, those factors which tended to be related to the response of runoff were present in the erosion models. The following equation had an R^2 of .861 and a standard error of the estimate of ± 0.587 lbs./acre.

$$E_r = -5.276 + 0.020P_a + 0.007E_u - 0.191S + 1.099T \qquad \text{(equation 3)}$$

where E_r is the ratio of pre- to post-fire erosion in pounds per acre. An increase in erosion following fire is indicated by a value below 1.0, which was generally the case. The variable E_u is the magnitude of the erosion on the unburned plot and indicated the normal potential for erosion.

The soil textural variable, T, this time has been quantified arbitrarily according to the judged relative porosity of the arrayed soil groups as listed in Table 2. An increase in T, a progression toward the coarser-textured soils, will result in reducing the erosion response of the plot to fire. Models derived from erosion plot data have been computed from a rather small number of observations. It is clearly evident that applying these models under conditions which would increase any of the (P_a), (E_u) or (T) input variables to their maximum limits would result in the prediction of a much higher erosion total for the unburned than the burned site. Although this is not entirely impossible (in some areas investigators have detected an increase in infiltration and a subsequent decrease in runoff and erosion following fire), it occurs only under a relatively rare combination of conditions. Additional research is indicated to establish the influence of these and other factors more precisely.

Watershed Studies

Because of the complexities associated with watershed studies, few investigations have been carried out using fire as a specific treatment. Few data are available from paired watersheds where suitable control measurements could be utilized. In addition, the only hydrologic factor for which adequate data could be brought together for statistical testing was peak discharge. Even then the number of publications furnishing information on more than four independent variables limited the generation of rational models of a higher order. It will suffice here to present the following closely-related equations developed from paired watershed data presented in only two publications. They represent but a limited geographic area and vegetative type, the chaparral country of southwestern United States.

$$RP_b = 0.009 + 9.992P_s + 7.233RP_u + 0.471A_b - 0.036A_t \qquad \text{(equation 4)}$$

The standard error for this equation was +15.196 csm (cubic feet per second per square mile) and the R^2 was 0.956. The number of observations available for the regression computation was only 12.

$$RP_b = 158.915 + 9.036P_s + 7.374\ RP_u - .132A_t - 3.498T_c \qquad \text{(equation 5)}$$

The standard error for this equation was $\pm$ 14.469 csm and the R^2 was 0.944. The number of observations this time was also 12.

In both of these cases, the relationships between the tested variables and the runoff peak response to fire are well established. However, the precision to which the models might be used to predict runoff peaks, even from burned watersheds similar in character and geographic origin to those used in the computation, is rather low (as expressed by the relatively large standard error of the estimates). This is a reflection of the complexity of the response of runoff peaks to many interacting variables.

The runoff peak following fire variable (RP_b in csm) was considered the most useful prediction of response especially since in the presented models it is strongly dependent on the peak discharge from the control watershed (RP_u).

In both models the runoff peak response is related inversely to the total size of the watershed (A_t). This relationship may be the result of the fact that in the studies watersheds the fires were confined to a relatively small portion of the total area. The effect of small fires on larger watersheds would logically be less. As the proportion or per cent of the total area which is burned becomes larger (A_b) the effect on runoff logically increases. As the soil texture becomes heavier, that is, a greater per cent clay in the named soil type (T_c), the modification of the litter cover and soil surface by fire becomes less important in terms of significantly changing its infiltration capabilities and resulting runoff.

Many factors such as the extent and type of forest or range cover, watershed morphometric characteristics, specific storm features, and characteristics of the associated fire, all which would undoubtedly influence the runoff response to burning, could not be considered in the statistical analysis because of a lack of adequate data. A more generally applicable model would necessarily include several of these additional variables.

DISCUSSION

The mathematical expressions presented here must not be taken to represent the precise universal relationships between the specific variables and the hydrologic response function. The limitations in the quantity and quality of available data, both in geographic origin and in the variables represented, restrict even the most general interpretation. The rather high statistical significance presented for most of the equations is undoubtedly a reflection of the limited variability in the data obtained from relatively few sources. A larger sample would probably yield a greater range in the specific quantities and more statistical variability.

Although the equations are generally limited in application beyond the geographic source of the data, significant relationships between the various factors and the hydrologic response to fire have been demonstrated. With ever-increasing demands being placed on the water resources of our wildlands, it seems essential that we learn as much as possible about the complex hydrologic response to so common an occurrence on many headwater watersheds as wildfire. The variables included above certainly would be important in determining the magnitude of the response anywhere and therefore should be considered in any local research undertaking. Other factors brought out in the literature, but for which there were insufficient data available for analysis, can be suggested.

In areas where fires are a common occurrence, future studies carried out on paired research watersheds should be designed to investigate the effects on the fire-hydrology response of (1) total watershed area, (2) area burned, (3) soil characteristics, (4) morphometric characteristics, (5) precipitation event characteristics, (6) location of the fire within the watershed, (7) antecedent precipitation, (8) fire intensity, (9) extent of vegetation and soil cover destruction, and (10) number of times burned.

Plot studies should be directed toward discovering basic quantitative relationships between the fire and hydrologic response and specific climatic, edaphic, physiographic, and vegetative variables. Results should have universal as well as regional application.

Future process studies should investigate the chemical and physical reactions which take place at the surface of the soil during and following fire.

As in the past, the stimulus for future research in this area will result from an awareness of the potential or demonstrated economic and social consequences of the fire-hydrology sequence. As stated before, the magnitude of these consequences will depend on the regional and local conditions prevailing. Past research has indicated that the effects of fire on wildland hydrology do not have to be harmful or even significant.

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