ESTIMATING THE EFFECTS OF WILDFIRE ON WATER SUPPLIES IN THE NORTHERN ROCKY MOUNTAINS

by

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INTRODUCTION

Wildfires during the summer of 1988 burned a significant portion of the watersheds in and around Yellowstone National Park. Several smaller wildfires also consumed isolated timbered areas in Western Montana. Even before the fires were under control, questions regarding the effects of the fires on streamflow volume were raised by water users and water management agencies in the region.

The Soil Conservation Service and National Weather Service share the responsibility for water supply forecasts in the Western U.S. A procedure was needed to estimate the effect of the wildfires on expected spring and summer streamflow volumes. More precisely, a procedure was needed to adjust the results of pre-fire calibrated forecast procedures to reflect post-fire conditions. The scale of the 1988 fire season in the Greater Yellowstone area was far beyond that of recent experience. As such, there was no observed precedent upon which to place the expected hydrologic effect of the fires.

BACKGROUND

Fires affect the hydrology of a watershed primarily through vegetation type conversion. Timbered areas are thinned or replaced by pre-climax species until regeneration restores the original vegetation. When the vegetation type is altered, the water balance of the site changes. Evapotranspiration and interception rates change. In timbered alpine watersheds, snowpack accumulation and ablation also change.

Although comprehensive case studies of the effects of burning on water yield are lacking, numerous studies have been made on the effect of timber harvest on water yield (Bosch and Hewlett, 1982). In 94 paired watershed studies, no water yield decreases were observed. Yet, the observed increases do not lend themselves towards a statistically significant universal rate of increase. Numerical generalizations are difficult because responses vary with the hydrologic regime. As such, procedures that predict watershed response must be specifically tailored to the hydrologic regime of the drainage.

A procedure for estimating the effects of fire on water yield in the Northern Rocky Mountains has been proposed (Potts, Peterson, and Zuuring, 1985). Yield increases were developed for various aspects and basal area losses using the WATBAL model (Leaf and Brink 1973a, 1973b) with regional coefficients. While this procedure holds a fair amount of promise, several factors prevented the direct use of the provided estimated water yield increases. As configured, the WATBAL model assumed that the existing cover in the pre-burn condition was maximum density. From this basis, percent basal area loss provides a reasonable index of canopy change. When the pre-burn condition is less than fully stocked, say 70 percent, the applicability of the suggested yield increases becomes questionable. Additionally, the authors are uncomfortable with the theory employed to explain differential open area snow accumulation (Hoover and Leaf, 1967). In spite of this, the WATBAL model may provide reasonable estimates of response once detailed site information becomes available. Severe time limitations and the availability of only rough preliminary site data precluded its' use at this time.

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Given the pressing need for enhanced runoff estimates and the lack of a readily applicable procedure, a procedure has been developed. The procedure is not a rigorous evaluation of the hydrologic effects of wildfire. The procedure is designed to provide an adjustment to the seasonal volume forecast. The hydrologic rigorousness of the procedure was limited by the rough nature of the preliminary site data and the limited time before its required use in the 1989 water year forecasts. The following is a description of the procedure.

GENERAL THEORY

The procedure is based on the premise that a reduction in timber canopy will result in reduced interception loss. Reduced interception loss enhances runoff by allowing for greater snowpack accumulation during the winter and greater precipitation throughfall during the spring. In timbered alpine watersheds, such as those burned in the Greater Yellowstone Area, the hydrologic regime is dominated by the accumulation and melt of the seasonal snowpack. Partial or total removal of the forest canopy by fire will alter the accumulation of the snowpack. Differences in snow accumulation between timbered and adjacent open areas is a well documented phenomenon and its' explanation has employed several theories during the past forty years. Recent studies indicate that the difference may be largely a function of reduced interception loss (Meiman, 1987).

In addition to enhanced snowpack accumulation, partial or total removal of the timber canopy will reduce interception losses during the spring when precipitation falls as rain. Fahey, et al. (1988) found that precipitation interception in a lodgepole pine forest (leaf area index = 9.9) in Southwestern Wyoming was roughly 27 percent. Wilm and Niederhoff (1941) measured a 70 percent throughfall rate for a mature lodgepole pine forest in Central Colorado.

The procedure does not directly consider the effect of vegetation type conversion on the evapotranspiration of soil water. It is not suggested that vegetation conversion does not effect evapotranspiration. Clearly this is the case. What is suggested is that early spring evapotranspiration is limited and late spring and summer evapotranspiration has a minor effect on the concurrent seasonal volume. Any reduction in summer evapotranspiration will probably have its' greatest effect on the following season's volume by providing a higher level of initial soil moisture.

Spring transpiration is unquestionably reduced when the timber canopy is removed. However, energy levels during at least the early portion of the spring are low and transpiration is limited. Differences in summer evapotranspiration are not included in the described procedure but are roughly accounted for by the pre-burn calibrated regression model. In burned areas, exposure and replacement vegetation will consume near surface soil moisture at a rate near that of the previously timbered site. Reduced soil moisture extraction at depths beyond the reach of replacement vegetation will likely contribute to enhanced yield via higher soil moisture levels carried into the following season. This contribution will not be realized in the first runoff season following the fire. Second and subsequent year enhancements are likely. The use of fall streamflow volume, as an independent variable in a multiple regression forecasting equation, may adequately account for this phenomenon as the variable acts as an index of antecedent soil moisture. Unfortunately, there is no guarantee that the fire hasn't altered the relationship between fall streamflow and that of the following spring and summer. This is certainly worthy of additional investigation in advance of the second runoff season.

The procedure itself draws on a set of physically based, empirical relationships developed from data collected in Western Montana and Northwestern Wyoming. These relationships are generalized for conditions experienced in the Northern Rocky Mountains. If sufficient information is available, it is wise to verify each relationship within the application watershed. If differences exist, relationships can be shifted to match local conditions. Application of these relationships outside the Northern Rocky Mountains may be possible but should be conditioned with local information.

PROCEDURE

The procedure is comprised of 5 steps:

1. Define the areas burned within the drainage of interest.
2. Estimate the pre-burn average annual streamflow.

3. Estimate the post-burn average annual streamflow.
4. Partition the estimated increase into the seasonal forecast period(s).
5. Apply the increase to the pre-burn calibrated forecast procedure results.

The example computations are for the watershed above Lower Willow Creek Reservoir near Hall, Montana. This watershed was chosen because its' analysis was the least lengthy of those burned during the summer of 1988. The procedure has been applied to the watersheds shown in Table 1 for use in the 1989 forecast season.

Table 1. Northern Rocky Mountain watersheds for which water supply forecasts were adjusted for the effects of the 1988 fires.

Watershed	Drainage Area (km2)	% Drainage Burned *
Clarks Fork Yellowstone River above Belfry, MT	2989	10
Gallatin River above Gallatin Gateway, MT	2137	7
Lower Willow Creek Reservoir Inflow near Hall, MT	189	9
Madison River above Grayling, MT	2344	38
Shoshone River above Buffalo Bill Reservoir, WY	3983	4
Snake River above Moran, WY	2090	36
Stillwater River above Absarokee, MT	2525	5
Sun River above Gibson Dam, MT	1489	7
Yellowstone River above Yellowstone Lake Outlet, WY	2605	25
Yellowstone River above Corwin Springs, MT	6794	31

* Preliminary figures. Only considers timbered areas with canopy burn.

Step 1. Define burned areas.

The first step is to isolate the forecast watershed and define the areas burned within it. Unless the forecast watershed is extremely small, pre- and post-burn conditions will not be uniform across the entire basin. Break the watershed into "burn units". Each burn unit will have the following common characteristics.

- pre-burn canopy density
- post-burn canopy density
- average annual precipitation

Find the area of each of the defined burn units. The average annual precipitation can be estimated from isohyetal maps prepared by the Soil Conservation Service or National Weather Service.

Step 2. Estimate the pre-burn average annual runoff.

For each burn unit, estimate the average annual runoff. A relationship between average annual precipitation and average annual runoff for streams in Western Montana is shown in Figure 1. (Farnes, 1971). Use Figure 1 to estimate the pre burn runoff for each burn unit as shown in Table 2. Note that the percent of average annual precipitation appearing as runoff is logged on the table. It will be used again later in the procedure. The total from Table 2 will be used to compute the estimated percent runoff enhancement from the burned areas.

Step 3. Estimate the post-burn average annual runoff.

Tables 3 and 4 show the computational process for this step and should be referred to as the procedure is described. The steps below are done for each burn unit.

Using average annual precipitation, the estimated April 1 open meadow snow water equivalent (SWE) can be estimated from the relationship shown in Figure 2 (Farnes, 1975). This is an estimate of April 1 SWE for the specific burn unit during an average year. Obviously there is a fair amount of uncertainty in this estimate. The following steps, however, evaluate the difference in how the pre- and post-burn canopy deals with the available snow. As such,

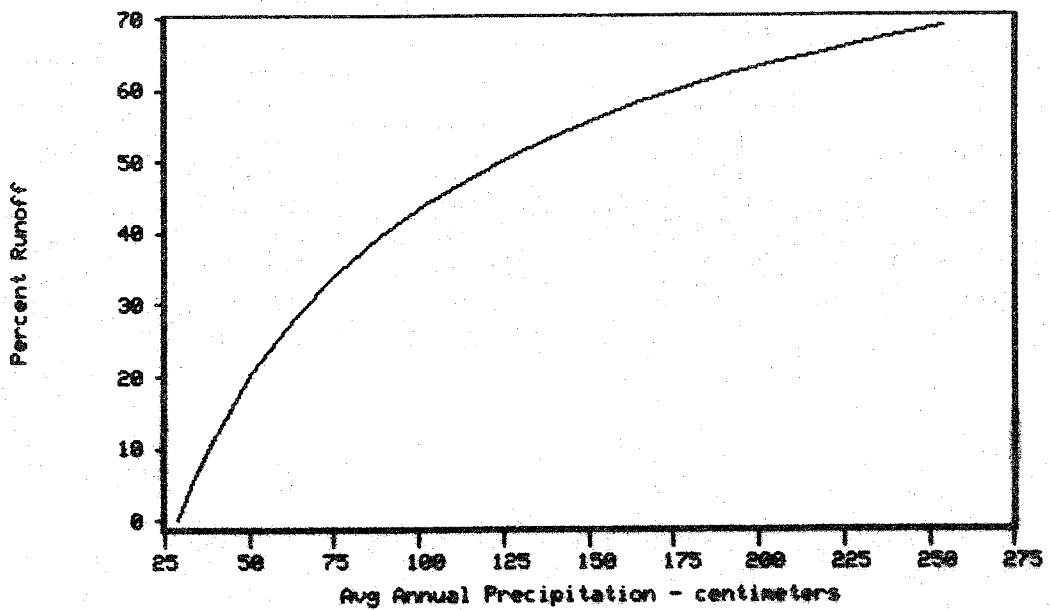

Figure 1. Average annual precipitation versus runoff percent. Computed from average annual runoff and average annual precipitation for watersheds in Western Montana and Northwestern Wyoming.

Table 2. Computational Worksheet. Pre-burn estimated runoff.

(1) Burn Unit	(2) Area (ha)	(3) Avg Ann Prec (cm)	(4) Percent Runoff	(5) Avg Ann RO (dam3)
1M	72.	73.7	33.8	180.3
2M	66.	71.1	32.7	153.3
3M	149.	71.1	32.7	347.1
4M	196.	73.7	33.8	488.5
4H	196.	73.7	33.8	488.5
5H	115.	66.0	30.2	229.9
6M	19.	63.5	28.9	34.1
7M	4.	63.5	28.9	6.7
8M	8.	63.5	28.9	14.1
9M	18.	66.0	30.2	36.3
10	13.	68.6	31.5	28.0
11H	651.	63.5	28.9	1193.7
12H	136.	66.0	30.2	270.3
13	21.	61.0	27.7	34.8
14M	7.	58.4	26.0	11.1
15H	5.	58.4	26.0	7.4
totals:	1676.			3524.1

the variability introduced by this estimate is diminished, provided the estimate is reasonably close.

As discussed earlier, the timber canopy can have a pronounced effect on the accumulation of snow. Analysis of snow course data collected primarily in lodgepole pine forests of Western Montana provided the relationship shown in Figure 3. Canopy density, in the case of Figure 3, is indexed by a 30 degree canopyometer measurement (Codd, 1959). Relationships similar to Figure 3 could be based on leaf area index or basal area. Additional samplings and canopyometer measurements were taken in Yellowstone National Park this winter to verify and refine this relationship. Using Figure 3, find the fraction of open area SWE expected under the pre- and post-burn canopy. Multiply the difference between these values by the average open area April 1 SWE to find the average enhancement to the April 1 SWE.

Table 3. Computational Worksheet. Post-burn estimated runoff enhancement due to increased snowpack.

(1) Burn Unit	(6) Avg Apr1 SWE (cm) (fig.3)	(7) Pre-Burn canopy density	(8) Pst-Burn canopy density	(9) Pre-Burn SC Factr (fig.4)	(10) Pst-Burn SC Factr (fig.4)	(11) SC Factr Change (10-9)	(12) Apr1 SWE Incr(cm) (11*6)	(13) Incr Ann Runoff (dam3)
1M	43.0	.70	.10	.65	.95	.30	12.9	31.5
2M	41.1	.95	.10	.52	.95	.43	17.5	37.7
3M	41.1	.80	.10	.60	.95	.35	14.4	70.3
4M	43.0	.85	.10	.57	.95	.38	16.1	106.8
4H	43.0	.85	.00	.57	1.00	.43	18.3	121.1
5H	37.5	.90	.00	.55	1.00	.45	16.9	58.8
6M	35.7	.95	.10	.52	.95	.43	15.2	8.2
7M	35.7	.95	.10	.52	.95	.43	15.2	1.6
8M	35.7	.95	.10	.52	.95	.43	15.2	3.4
9M	37.5	.85	.10	.57	.95	.38	14.1	7.7
10	39.3	.70	.05	.65	.98	.33	12.8	5.2
11H	35.7	.75	.00	.62	1.00	.38	13.4	251.7
12H	37.5	.75	.00	.62	1.00	.38	14.1	57.6
13	33.9	.95	.05	.52	.98	.45	15.3	8.7
14M	32.1	.95	.10	.52	.95	.43	13.6	2.6
15H	32.1	.95	.10	.52	.95	.43	13.6	1.7
total:								774.7

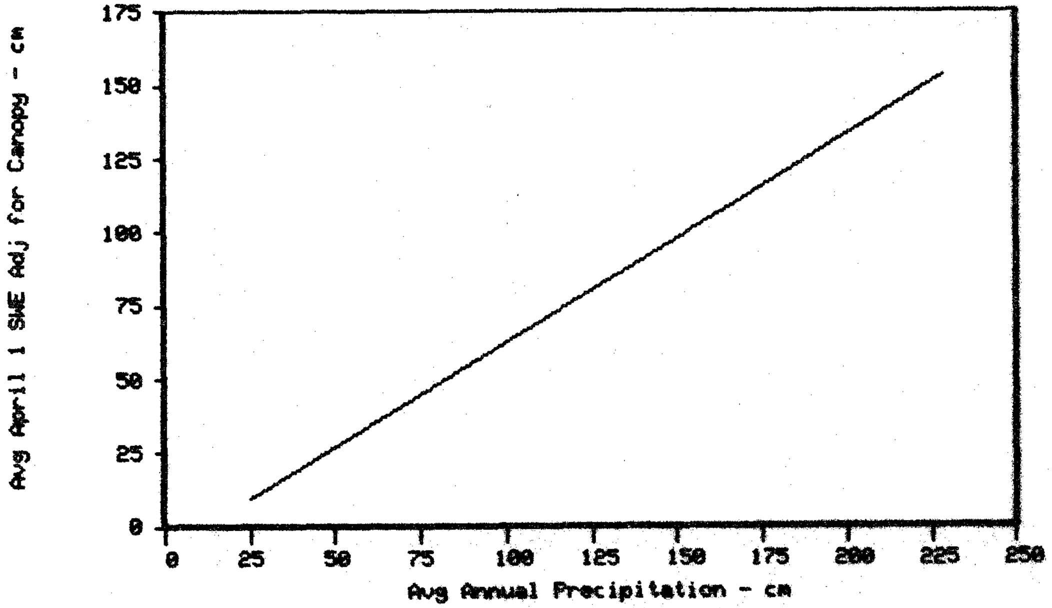

Figure 2. Average annual precipitation versus average April 1 snow water equivalent. Developed from information collected in Western Montana and Northwestern Wyoming.

To find the runoff enhancement due to increased April 1 SWE, multiply the increase in SWE by the percent runoff used in Step 2. Then convert the depth to volume based on the area of the burn unit. The use of the percent runoff from Step 2 most likely represents the lower bounds of the expected response. Chances are good that the enhanced SWE will run off with greater than average efficiency. For simplicity and realizing the eventual estimate from this procedure will be conservative, the average pre-burn runoff rate is used here.

In much the same way that the timber canopy reduces the snowpack on the ground beneath it, the timber canopy reduces the throughfall of precipitation to the ground surface. Figure 4 was developed from information provided in Fahey, et al. (1988). License was taken to

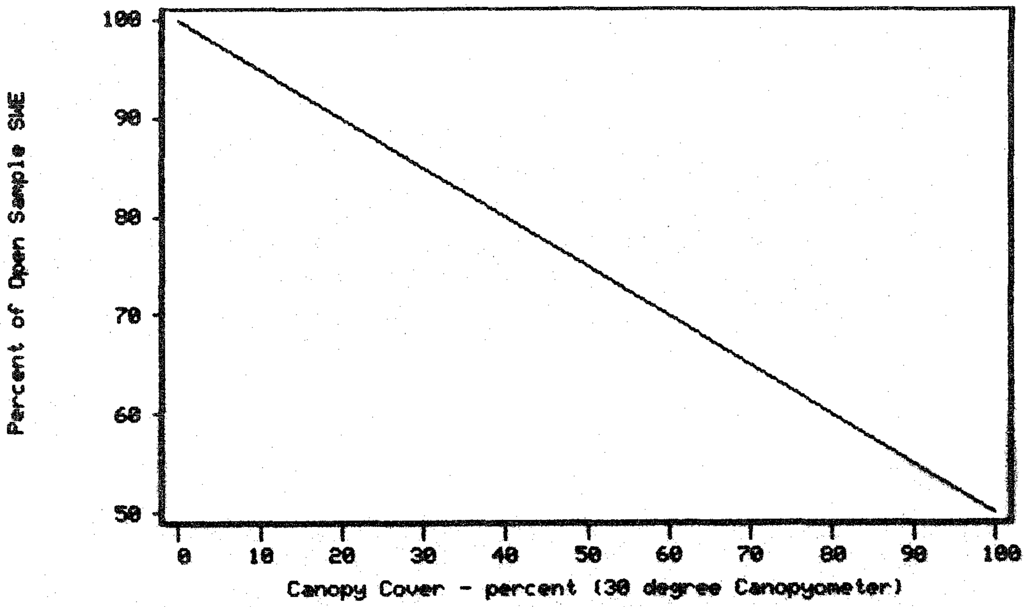

Figure 3. Canopy cover versus percent of adjacent open area snow water equivalent. Developed from information collected in Western Montana and Northwestern Wyoming.

Table 4. Computational Worksheet. Post-burn estimated runoff enhancement due to increased spring precipitation throughfall and total annual runoff increase.

(1) Burn Unit	(14) Spr Prec %	(15) Spr Prec (cm) (2*14)	(16) Pre-Burn Thrufall (fig.4)	(17) Pst-Burn Thrufall (fig.4)	(18) Thrufall Change (17-16)	(19) Thrufall Incr(cm) (18*15)	(20) Incr Ann Runoff (dam3)	(21) Totl Inc Ann RO (dam3)
1M	31.	22.8	.79	.97	.18	4.1	10.1	41.6
2M	31.	22.0	.71	.97	.26	5.6	12.1	49.8
3M	31.	22.0	.76	.97	.21	4.6	22.6	92.9
4M	31.	22.8	.74	.97	.23	5.1	34.1	140.9
4H	31.	22.8	.74	1.00	.26	5.8	38.6	159.7
5H	31.	20.5	.73	1.00	.27	5.5	19.2	78.0
6M	31.	19.7	.71	.97	.26	5.0	2.7	10.9
7M	31.	19.7	.71	.97	.26	5.0	.5	2.1
8M	31.	19.7	.71	.97	.26	5.0	1.1	4.5
9M	31.	20.5	.74	.97	.23	4.6	2.5	10.3
10	31.	21.3	.79	.99	.20	4.1	1.7	6.9
11H	31.	19.7	.77	1.00	.23	4.4	83.3	335.0
12H	31.	20.5	.77	1.00	.23	4.6	18.9	76.4
13	31.	18.9	.71	.99	.27	5.1	2.9	11.6
14M	31.	18.1	.71	.97	.26	4.6	.9	3.5
15H	31.	18.1	.71	.97	.26	4.6	.6	2.3
totals:							251.8	1026.4

assume a linear relationship of interception between the fully open and the fully closed timber canopy conditions. While more work is needed to precisely define this relationship, Figure 4 provides a simple avenue to the required estimates. The fraction of the average annual precipitation that normally occurs during the spring period can be computed from representative precipitation measurement sites in the general area. The seasonal distribution of precipitation can be quite different at high and low elevation sites. Sites selected for this analysis should be in a climatic regime similar to that of the burn unit. From Figure 4 find the difference in the throughfall rate for the pre- and post-burn conditions. Multiply this fraction by the average spring (April-June) precipitation to find the spring precipitation enhancement. To find the runoff enhancement due to increased

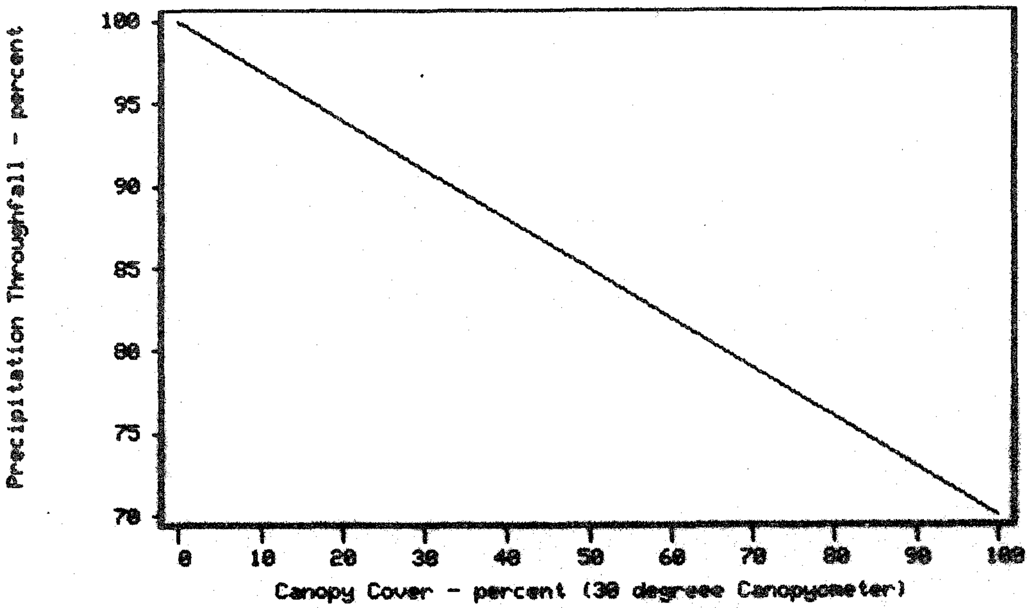

Figure 4. Canopy cover versus precipitation throughfall.

spring precipitation reaching the ground, multiply the enhancement by the runoff percent used in Step 2. Then convert the depth to volume based on the area of the burn unit.

Combine the increased runoff due to enhanced snowpack accumulation and spring precipitation throughfall to find the estimated total annual increase. Add the enhancement from all of the burn units within the forecast watershed to find the total annual runoff increase expected in an average year.

Step 4. Partition the average annual runoff increase into the forecast period(s).

In the Northern Rockies, water supply forecasts are normally provided for the April-July and April-September periods. As expected, the bulk of the increase in expected runoff will occur during the April-July forecast period. The portion of the estimated annual increase expected to occur in the April-July period varies from watershed to watershed. Some watersheds are less responsive than others and a larger portion of the runoff generated in the spring appears at the watershed outlet in late summer, fall, or even the following winter. To evaluate the seasonal relationships of a watershed, the historical April-July volumes were regressed against each of the subsequent monthly volumes, August through March. Significant slopes are summed for the August-March, August-September and October-March periods. The percentage of estimated annual increase expected in each of the seasonal periods is then computed as follows.

let $S1$ = sum of significant slopes August-March
$S2$ = sum of significant slopes August-September
$S3$ = sum of significant slopes October-March

April-July = $100 * 1/(1 + S1)$
April-September = $100 * (1 + S2)/(1 + S1)$
October-March = $100 * S3/(1 + S1)$

Table 5 shows the monthly slopes, Student's t and analysis for Lower Willow Creek near Hall, Montana.

From this analysis, multiply the estimated annual increase in volume by the period percentage to find the estimated increase for each of the forecast periods. This volume is then converted to a percentage of the average period volume. Sample computations are shown in Table 6.

Step 5. Application of Estimated Runoff Enhancement to Forecasts.

Percentage increases as shown in Table 6 can then be applied to the results of the forecast procedure. For example, if the regression model for the forecast point in Table 6 indicated

Table 5. Period analysis of Lower Willow Creek near Hall, Montana. 19 years of data.

Month	Slope	t		
August	0.014	2.67	Sum of Slopes:	Aug-Mar = 0.057
September	0.008	1.64		Aug-Sep = 0.022
October	0.015	2.44		Oct-Mar = 0.035
November	0.006	0.82*		
December	0.020	2.74	Period Percentages:	Apr-Jul = 94.6%
January	0.006	0.95*		Apr-Sep = 96.7%
February	0.003	0.46*		Oct-Mar = 3.3%
March	0.000	0.00*		

* not significant

Table 6. Computation of percent increase by forecast period. Lower Willow Creek near Hall, Montana.

	Burned Area		Total Watershed	
Period	Average Volume (dam3)	Est. Incr. (percent)	Average Volume (dam3)	Est. Incr. (percent)
Annual	3524	22.7	22849	3.2
April-July	2613	29.0	18425	4.1
April-September	2767	28.0	19514	4.0

an April-July volume of 16000 dam3 (87 percent), it would be adjusted to 16660 dam3 (90 percent) to account for the effects of the 1988 fires. Dealing with the runoff enhancement as a percent evaluated at the average vastly simplifies the analysis and makes an acceptable amount of sense. High years will experience greater runoff enhancement than low years and the application of the percentage to the actual forecast should account for the bulk of this differential response. If anything the procedure will tend to over estimate the response in extremely low years and under estimate it in extremely high years.

It should be noted that the runoff enhancement due to reduced summer evapotranspiration is not included in the final figures as shown in Table 6. Reduced summer evapotranspiration will result in a higher level of post-summer soil moisture and in turn a higher level of runoff during the following season. Multiple regression models can account for variation in antecedent soil moisture through the use of fall runoff volume as an independent variable. Higher fall streamflows infer a higher level of soil moisture in watershed. As such, the pre-burn calibrated forecast procedure will account for a portion of the enhancement and the remaining adjustment is provided by the described procedure.

As time passes, the burned watersheds will regenerate their timber canopies and the estimated enhancements will gradually disappear. An analysis of this attenuation has not been addressed at this time. However, since this procedure is indexed to canopy closure, the full estimated enhancement can be expected to continue for a minimum of five to ten years.

APPLICATION

The described procedure has been applied to each of the watersheds shown in Table 1. The results are shown in Table 7.

Interestingly, the values derived with this procedure are quite similar to those proposed by Potts, Peterson, and Zuuring (1985). Reduced summer evapotranspiration will likely result in higher fall streamflows in water year 1990. A review of regression procedures in the Yellowstone area indicates a 10 percent increase in fall runoff leads to a 1.5 to 2.0

percent increase in the April-July volume.

Table 7. Estimated seasonal runoff enhancements for Northern Rocky Mountain watersheds burned during the summer of 1988.

Watershed	Estimated Runoff Enhancement (%) April-July	Estimated Runoff Enhancement (%) April-September
Clarks Fork Yellowstone River above Belfry, MT	3.0	3.0
Gallatin River above Gallatin Gateway, MT	2.6	2.5
Lower Willow Creek Reservoir Inflow near Hall, MT	3.8	4.1
Madison River above Grayling, MT	13.1	12.2
Shoshone River above Buffalo Bill Reservoir, WY	2.1	2.0
Snake River above Moran, WY	10.6	10.4
Stillwater River above Absarokee, MT	2.0	2.0
Sun River above Gibson Dam, MT	1.5	1.6
Yellowstone River above Yellowstone Lake Outlet, WY	8.6	8.2
Yellowstone River above Corwin Springs, MT	9.8	9.5

VERIFICATION

Verification of estimates generated with this procedure will not be a quick or simple task. In most cases, the standard error of adjacent basin relationships and forecast procedures approaches the magnitude of the enhancement. Therefore, it will be difficult to verify the accuracy of the procedure after only one or two forecast seasons. Objective evaluations will be simple only if the observed effects far exceed the estimates produced by this procedure.

SUMMARY

A procedure for estimating the effects of wildfire on streamflow volume in the Northern Rocky Mountains has been described. The procedure is designed to provide an adjustment to forecast results generated with a pre fire calibrated regression model. The procedure is based on the premise that a reduction in timber canopy will result in reduced winter snow and spring precipitation interception which will in turn lead to enhanced streamflow volume. It is proposed that any reduction in summer evapotranspiration will manifest its' effects in the following runoff season via higher levels of antecedent soil moisture. Multiple regression models can account for variability in antecedent soil moisture and therefore should account for the effect of reduced summer evapotranspiration without adjustment.

The procedure operates with a series of empirical relationships derived from data gathered in Western Montana and Northwestern Wyoming. The procedure is not a rigorous evaluation of the hydrologic effects of fire. Its simple form and compatibility with the rough nature of preliminary site information allowed for its application in the 1989 water supply forecast season. The availability of estimates for the 1989 water year was critical. As the lead agency for the collection and analysis of snow information, the Soil Conservation Service in cooperation with the National Weather Service, is committed to providing the best possible water supply information to its' clients in the Western U.S.

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