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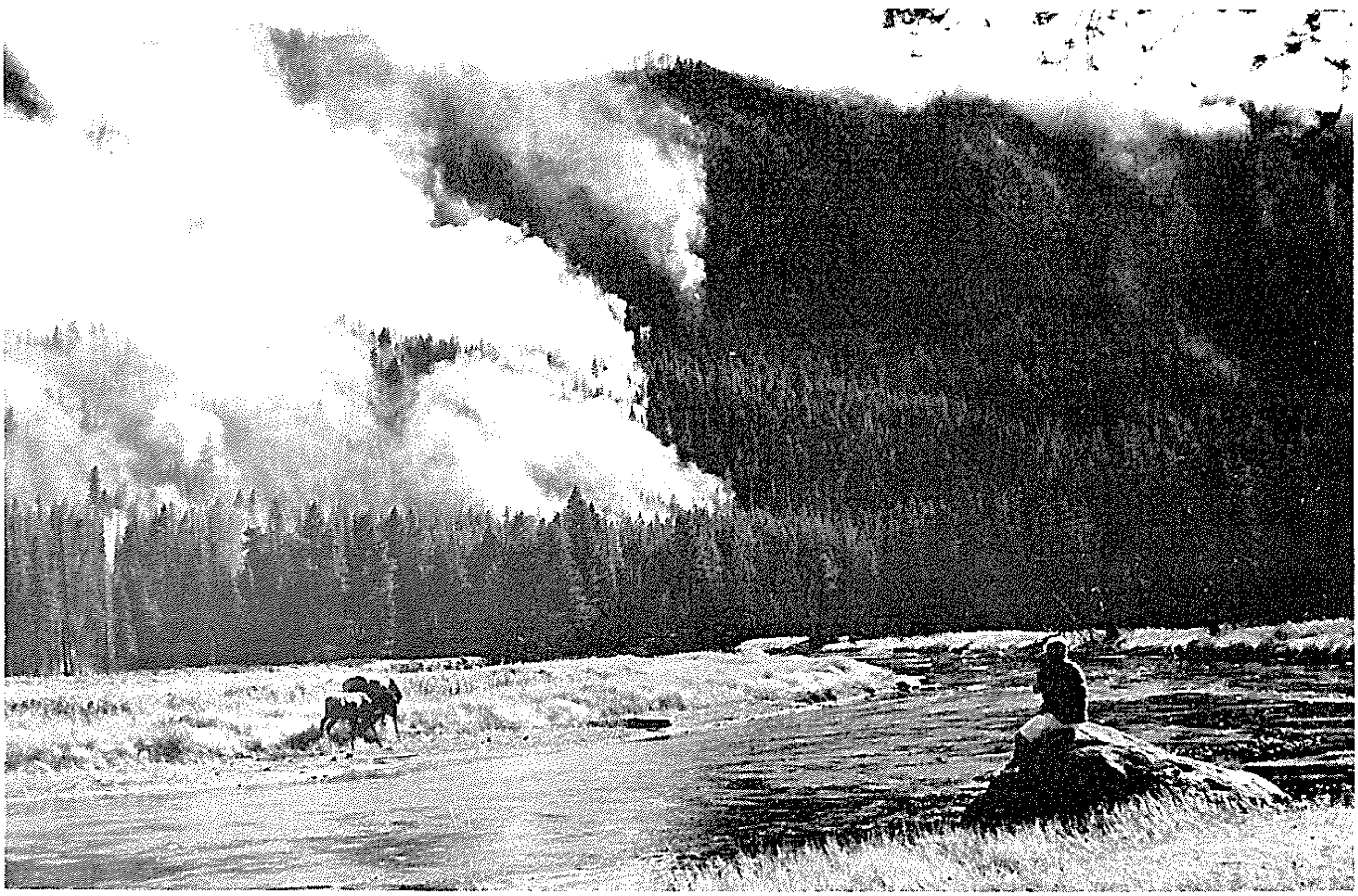
Estimating Postfire Water Production in the Pacific Northwest

Donald F. Potts **David L. Peterson** **Hans R. Zuuring**



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Two hydrologic models were adapted to estimate postfire changes in water yield in Pacific Northwest watersheds. The WRENSS version of the simulation model PROSPER is used for hydrologic regimes dominated by rainfall; it calculates water available for streamflow on the basis of seasonal precipitation and leaf area index. The WRENSS version of the simulation model WATBAL is used for hydrologic regimes dominated by snowfall; it calculates water available for streamflow based on seasonal precipitation, energy aspect, and cover density. The PROSPER and WATBAL models estimate large postfire increases in water available for streamflow only for fires that have removed more than 50 percent of the leaf area or cover density, respectively. Guidelines for selecting appropriate models, and tables and figures for calculating postfire water yield are presented. This simulation approach should be useful for estimating long-term effects of fire on water production within the framework of land management planning.

Retrieval Terms: fire effects, hydrologic models, simulation models, watershed

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Wildfire annually burns thousands of acres of Pacific Northwest watersheds and can affect the quantity and quality of water resources. Fire often produces an increase in water yield which may persist for many years.

It is difficult to accurately predict this postfire increase in water production. Nevertheless, estimates of effect of fire on resource outputs are needed for land management planning. These estimates should be long-term and of a broad resolution (not site-specific). Land managers and fire managers currently do not have the capability to generate these estimates for forested watersheds.

A methodology is presented here in which site-specific hydrologic models were adapted to provide the estimates of postfire water yield needed for fire management planning. The hydrologic models were adapted from the publication "An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook)" (WRENSS). Critical elements of the models are discussed with respect to modeling objectives.

Two basic models—PROSPER and WATBAL—were used, both of which rely heavily on estimation of seasonal evapotranspiration. As modified for use in WRENSS hydrology, the PROSPER model is to be applied in areas in which rainfall is the dominant form of precipitation. The WRENSS version of PROSPER calculates the amount of water available for annual streamflow on the basis of the amount of seasonal precipitation and the post-disturbance residual leaf area index. Model output indicated that large increases in streamflow are produced only if more than 50 percent of the leaf area of a stand is removed.

Also adapted for WRENSS hydrology, the WATBAL model is to be applied in areas in which snowfall and snowpack development dominate annual precipitation. The WRENSS version of WATBAL calculates water available for streamflow on the basis of the amount of seasonal precipitation, energy aspect, and residual cover density (which may be estimated by basal area). Model output again indicated that water yield increases are minimal until basal area loss to fire exceeds 50 percent.

Tables and diagrams are presented for calculating water available for annual streamflow after fire for different watershed conditions in the Pacific Northwest. Guidelines are also given for selecting the appropriate precipitation regime and model.

INTRODUCTION

Wildfire on forested watersheds in the Pacific Northwest can increase water production for several years after fire. Water yield is a valuable resource for agriculture, municipal and industrial use, and generation of hydroelectric power in this region. Increases in water yield are economically beneficial as long as they are not accompanied by flooding or excessive sediment production.

Fire management programs on National Forest lands are required to be integrated with forest land management plans and should be cost-effective (Nelson 1979; U.S. Dep. Agric., Forest Serv. 1979). Resource managers involved in planning need to know the effect of long-term changes in water production and in the value of water caused by wildfire.

The effects of fire on water in ecosystems of the Pacific Northwest and other regions are well-documented (Tiedemann and others 1979). Nearly all of this information is site-specific, however, and it is difficult to extrapolate data from one site to another because of differences in soils, vegetation, and other site factors. Despite site differences, several generalizations can be made about the response of water resources to wildfire. Removal of vegetation by fire leads to temporarily reduced evapotranspiration, increased overland flow, and greater peak and total discharge. These changes in basic hydrologic processes can lead to increased sensitivity of the landscape to erosion and provide pathways for increased sediment losses from watersheds (Tiedemann and others 1979).

Several hydrologic models have been developed to simulate watershed processes and water production under different conditions. The most commonly used models are deterministic and site-specific, none of which was intended to be used at the broad level of resolution that is particularly useful in fire management planning. In 1985, we developed a technique for estimating postfire water production at a level of resolution suitable for fire management planning (Potts and others 1985). We adapted the Water Resources Evaluation of Non-Point Silvicultural Sources (WRENSS) (U.S. Dep. Agric., Forest Serv. 1980) water yield models to provide estimates of postfire water yield in the northern Rocky Mountains. The models were simplified and generalized such that users would need to specify only annual precipitation, aspect, and stand basal area removed by fire in order to estimate both short-term and long-term changes in water production.

This paper describes the adaptation of the WRENSS water yield models to produce broad resolution estimates of expected changes in postfire water yield for the diverse hydrologic regimes of the Pacific Northwest. The basic algorithms and assumptions of these simulation models are described, and important model inputs are discussed. Expected changes in water yield after fire are calculated for watersheds with different physical, vegetative, and hydrologic characteristics.

METHODS

Water Yield Modeling

The water yield models used in this paper are adapted from Chapter III in "An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook)" (WRENSS) (U.S. Dep. Agric., Forest Serv. 1980). In this paper we focus only on elements of the water yield models that are critical to our modeling objectives. Detailed descriptions of derivations and assumptions used in the construction of the water yield models are included in the WRENSS documentation. We used WSDU*WATER.WET, the computerized version of the WRENSS water yield models. Computer model documentation and sensitivity analyses (Daddow and Williams 1984, Williams and Daddow 1984) provide further insight into the structure and operation of the WRENSS water yield models.

A generalized flow diagram shows the major components of the WRENSS water yield models (*fig. 1*). The following discussion of decision points, procedural step computations, and data inputs corresponds closely to this flow diagram.

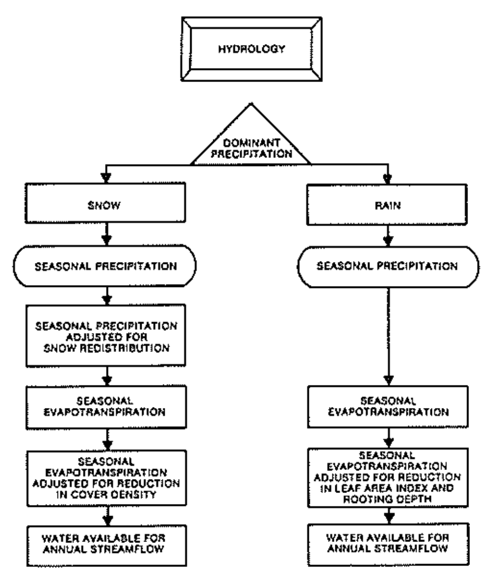

Figure 1—The major components of WRENSS hydrology.

Dominant Precipitation

The WRENSS water yield model for areas in which rainfall is the dominant form of precipitation differs from the WRENSS water yield model for areas in which melting snowpack accounts for most of annual streamflow. In the mountains of the Pacific Northwest, it is sometimes difficult to decide which model is appropriate to use, but WRENSS documentation provides some general guidelines for model selection. In most of the Pacific Northwest, rainfall is the dominant form of precipitation below an elevation of about 1250 m. The WRENSS adaptation of the water yield model PROSPER (Goldstein and others 1974) should be applied for simulations in this rain-dominated regime. The WRENSS adaptation of the water yield model WATBAL (Leaf and Brink 1973) should be applied for simulations at elevations above 1250 m, at which snowpack development and melt are more important hydrologically.

Seasonal Precipitation

Snow—WATBAL calculates evapotranspiration by season, and seasonal dates can vary by region. The chief purpose of distinguishing among seasons is to isolate winter (the period of snowpack development and melt) from the other seasons. For the western portions of Washington and Oregon, WATBAL breaks winter further into two sub-seasons. The four increments of time used in simulation are:

Early winter: October 1 to December 29
Late winter: December 30 to March 28
Spring: March 29 to June 26
Summer and fall: June 27 to September 30

WRENSS documentation recommends a single winter season for eastern Washington and Oregon, but we found little difference in water yield estimates for this region using a single winter season or two winter sub-seasons.

We looked at long-term climatological data for higher-elevation stations in the Pacific Northwest and chose the following representative seasonal distribution of average annual precipitation for simulations:

Early winter: 40 percent
Late winter: 35 percent
Spring: 15 percent
Summer and fall: 10 percent

Note that early and late winter precipitation—the majority of which would be snowfall—accounts for 75 percent of average annual precipitation.

Seven annual precipitation classes were used in the simulations. The lowest average annual precipitation was 60 cm, and classes increased in 30-cm increments to 240 cm. Many locations in the Pacific Northwest have average annual precipitation greater than 240 cm, but, as will be seen later, greater amounts of precipitation are all in excess of evapotranspiration and therefore translate directly into runoff. The seven classes of average annual precipitation were then distributed into average seasonal precipitation using the percentages discussed above.

For example:

if average annual precipitation = 60 cm,
then early winter precipitation = 24 cm,
late winter precipitation = 21 cm,
spring precipitation = 9 cm,
summer/fall precipitation = 6 cm.

Rain—PROSPER, like WATBAL, calculates evapotranspiration by season. Summer is represented by June, July, and August; fall by September, October, and November; winter by December, January, and February; and spring by March, April, and May. Snow will occur in winter, early spring, and late fall at low elevations in the Pacific Northwest, but snowpack development is rare and short-lasting when it occurs.

The seasonal distribution of annual precipitation chosen for the simulations was:

Winter: 40 percent
Spring: 20 percent
Summer: 10 percent
Fall: 30 percent

As with the WATBAL simulations, seven annual precipitation classes ranging from 60 cm to 240 cm, in 30-cm increments, were chosen. Each annual precipitation class was then distributed into seasonal precipitation with the percentages discussed above.

Adjustment for Snow Redistribution—The maritime influence on the climate of the Pacific Northwest decreases with distance from the Pacific Ocean, but even in Eastern Washington and Oregon, the relatively high-density snowfall is not redistributed significantly. Seasonal precipitation is therefore not adjusted for redistribution in these simulations.

Seasonal Evapotranspiration

Snow—Energy availability strongly controls snow processes. WATBAL addresses this physical reality by determining seasonal evapotranspiration by energy aspect. South aspects have the greatest energy availability and therefore the highest evapotranspiration in any season. North aspects have the lowest energy availability, and east-west aspects have intermediate energy availability.

WATBAL also expresses seasonal evapotranspiration as a function of seasonal precipitation. Simulated evapotranspiration is strongly precipitation-dependent at low precipitation levels, except in the early and late winter seasons when precipitation is never limiting.

Baseline seasonal evapotranspiration (no canopy removal) ranged from a low of 3 cm on north aspects in late winter in any of the annual precipitation classes to 27.9 cm on south aspects in summer and fall when annual precipitation was 150 cm or more.

Rain—PROSPER estimates of seasonal evapotranspiration are different from those of WATBAL. Unlike the case for snow-dominated regions, the PROSPER simulations do not show any direct relationship between amount of precipitation and evapotranspiration losses. Precipitation in the Pacific Northwest is generally adequate to maintain near-potential evapotranspiration rates.

The other major difference between evapotranspiration estimates for the rain and snow models is the lack of sensitivity to aspect exhibited by PROSPER. Seasonal evapotranspiration is the same on all aspects. The WRENSS adaptation of PROSPER does this because, before 1980, only one experimental study (Swift and others 1975) had isolated the effects of aspect on evapotranspiration. Evapotranspiration was observed to be only about 5 percent higher on south aspects than on north aspects. It was decided that, given the other simplifications in the WRENSS modeling approaches, it was not necessary to account for such small differences.

Seasonal Evapotranspiration Adjustment

Snow—"Cover density represents the efficiency of the three-dimensional canopy system to respond to energy input. It varies according to crown closure, vertical foliage distribution, species, season and stocking" (U.S. Dep. Agric., Forest Serv. 1980, p. III.88). Cover density cannot be measured directly, but WRENSS documentation provides relationships between cover density of major commercial species and a more common mensurational parameter, basal area.

Evapotranspiration adjustment is necessary because, as trees are removed from a stand (basal area is reduced), the evaporating and transpiring aerial surface area is proportionally reduced and the forest floor becomes progressively more exposed. The pre-disturbance condition defines the *Baseline Forest Cover Density*, CD_{max} (percent). Seasonal evapotranspiration is adjusted by the ratio of residual (post-disturbance) cover density (CD) to the baseline condition (CD_{max}). For these simulations it is assumed that pre-disturbance cover density is the baseline condition and represents complete hydrologic utilization.

This paper presents simulation of five conditions of cover density expressed as basal area reduction: 0 percent (baseline), 50 percent, 65 percent, 90 percent and 100 percent. We assumed a pre-disturbance basal area of 300 ft^2/ac (70 m^2/ha). This value is representative of many mature hemlock-spruce or Douglas-fir stands in the Pacific Northwest, but apparently is relatively unimportant as an absolute number in the WRENSS model. We found that 50 percent and 90 percent reduction of basal area from initial basal areas between 250 and 350 $ft^2/acre$ (60 to 80 m^2/ha) produced ratios of cover density to cover density maximum (CD/CD_{max}) within 10 percent of each other.

Baseline seasonal evapotranspiration was adjusted after the pre- and post-disturbance cover density relationships were obtained. WRENSS documentation includes figures (III.54 and III.55) that provide evapotranspiration modifier coefficients for the Pacific Northwest. *Table 1* summarizes these figures from WRENSS and displays evapotranspiration modifier coefficients by season, aspect, and residual stand basal area as used in this analysis. Modifier coefficients in the late winter for all aspects and in spring for north aspects become greater than 1 as cover

Table 1—*Evapotranspiration modifying coefficients at various residual stand basal areas, by season and energy aspect, used in the snow-dominated model WATBAL. For initial stand basal areas of 45 to 80 m^2/ha, residual basal area classes correspond to 1.0, 0.75, 0.5, 0.2 and 0 times baseline cover density*

Season	Aspect[1]	Percentage of stand basal area after fire				
		100	50	35	10	0
Early winter	S	1.00	1.00	1.00	0.73	0.55
	E/W	1.00	1.00	1.00	0.73	0.55
	N	1.00	1.00	1.00	0.73	0.55
Late winter	S	1.00	1.13	1.25	1.04	0.90
	E/W	1.00	1.18	1.33	1.10	0.96
	N	1.00	1.24	1.45	1.17	1.00
Spring	S	1.00	1.00	1.00	0.73	0.55
	E/W	1.00	1.00	1.00	0.94	0.88
	N	1.00	1.00	1.00	1.15	1.25
Summer	S	1.00	1.00	1.00	0.77	0.62
	E/W	1.00	1.00	1.00	0.73	0.55
	N	1.00	1.00	1.00	0.65	0.4

[1]S, south; N, north; E/W, east and west.

density is reduced. In general, total evapotranspiration losses increase as basal area is removed.

In our simulations, increase in late winter evapotranspiration produced a net decrease in predicted annual water yield on all aspects and precipitation classes when 50 percent of the initial basal area was removed.

Rain—PROSPER uses leaf area index (L.A.I.), the ratio of total leaf surface area to ground surface area, to index total transpiring and evaporating surface. On the basis of previous studies (Kaufmann and others 1982, Gholz and others 1979), we assumed a leaf area index of 40 in model simulations of undisturbed sites, and that there was a linear relationship between stand basal area and total leaf area index. The undisturbed basal area of 70 m^2/ha used in the WATBAL simulations is consistent with a leaf area index of 40 for mature conifer stands in the Pacific Northwest and central Rocky Mountains (Gholz and others 1979, Kaufmann and others 1982). *Table 2* shows baseline evapotranspiration and evapotranspiration modifiers for various stand leaf area indices by season as used in the PROSPER analysis.

Dry sites may carry less leaf area than we assumed for our undisturbed stand simulations, but an undisturbed site with a leaf area index of 20 (and basal area of 35 m^2/ha) exhibits only 6 percent less total evapotranspiration than the site with a leaf area index of 40 *(fig. 2, table 2)*. These numbers are consistent with the WATBAL simulations that predicted very little change in water yield (actually a small decrease) when 50 percent of the basal area was removed from the stand.

PROSPER is sensitive to rooting depth, and allows the use of an evapotranspiration-modifying coefficient if soil depth is less than or greater than 1 m. This is, of course, very site-specific information. Therefore, we assume a 1 m average soil depth for all simulations and therefore, offer no modification of seasonal evapotranspiration for rooting depth.

Table 2—*Baseline evapotranspiration and evapotranspiration modifiers for various leaf area indices by season used in the rain-dominated model PROSPER*

Season	Baseline evapotrans-piration	Stand leaf area index				
		40	20	10	4	1
	cm					
Fall	24.0	1.00	0.98	0.95	0.85	0.53
Winter	18.1	1.00	0.85	0.68	0.45	0.27
Spring	30.5	1.00	0.92	0.80	0.57	0.24
Summer	26.1	1.00	0.99	0.98	0.88	0.57

RESULTS AND DISCUSSION

The difference between seasonal precipitation and seasonal evapotranspiration provides an estimate of seasonally available water for streamflow in both WATBAL and PROSPER. Estimates of seasonally available water for runoff for both rain-dominated and snow-dominated regimes are summarized in *tables 3* and *4*. Seasonally available water for runoff is summed in each precipitation class to produce an estimate of

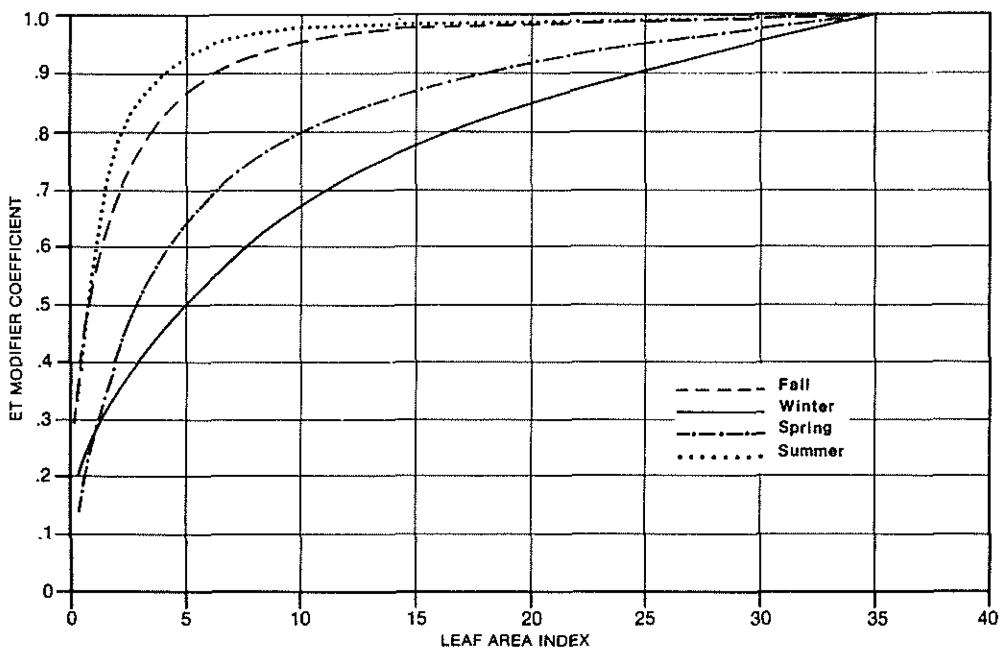

Figure 2—The WRENSS version of PROSPER uses coefficients to modify evapotranspiration (ET) on the basis of leaf area index (LAI) and season.

available water for runoff on an annual basis.

PROSPER estimates water available for annual runoff as a function of initial and residual leaf area indices and annual precipitation (*fig. 3*). WATBAL estimates water available for annual runoff as a function of basal area, average annual precipitation, and energy aspects (*figs. 4, 5* and *6*).

Earlier in our discussion, we offered guidelines for selecting the appropriate model for water yield estimates. Defining the upper boundary of the "transient snow zone" (Harr 1981) is actually somewhat problematical. To illustrate the problem, consider a hypothetical undisturbed watershed in this transition

Table 3—*Amount of water available seasonally for streamflow, calculated by PROSPER as the difference between seasonal precipitation and seasonal evapotranspiration in rain-dominated regions*

Precipitation (cm)		Seasonally available water for runoff (cm)[1]				
Total	Seasonal[2]	LAI=40[3]	LAI=20	LAI=10	LAI=4	LAI=1
60	F 18	-6.0	-5.5	-4.8	-2.3	5.3
	W 24	5.9	8.6	11.8	15.9	19.1
	Sp 12	-18.5	-16.0	-12.4	-6.6	4.6
	S 6	-20.1	-19.8	-19.4	-17.0	-8.8
	Annual total =	0.0	0.0	0.0	0.0	20.2
90	F 27	3.0	3.5	4.2	6.7	14.3
	W 36	17.9	20.6	23.8	27.9	31.1
	Sp 18	-12.5	-10.0	-6.4	0.6	10.6
	S 9	-17.1	-16.8	-16.4	-14.0	-5.8
	Annual total =	0.0	0.0	5.2	21.2	50.2
120	F 36	12.0	12.5	13.2	15.7	23.3
	W 48	29.9	32.6	35.8	39.9	43.1
	Sp 24	-6.5	-4.0	-0.4	6.6	16.6
	S 12	-14.1	-13.8	-13.4	-11.0	-2.8
	Annual total =	21.3	27.3	35.2	51.2	80.2
150	F 45	21.0	21.5	22.2	24.7	32.3
	W 60	41.9	44.6	47.8	51.9	55.1
	Sp 30	-0.5	2.0	5.6	12.6	22.6
	S 15	-11.1	-10.8	-10.4	-8.0	0.2
	Annual total =	51.3	57.3	65.2	81.2	110.2
180	F 54	30.0	30.5	31.2	33.7	41.3
	W 72	53.9	56.6	59.8	63.9	67.1
	Sp 36	5.5	8.0	11.6	18.6	28.6
	S 18	-8.1	-7.8	-7.4	-5.0	3.2
	Annual total =	81.3	87.3	95.2	111.2	140.2
210	F 63	39.0	39.5	40.2	42.7	50.3
	W 84	65.9	68.6	71.8	75.9	79.1
	Sp 42	11.5	14.0	17.6	24.6	34.6
	S 21	-5.1	-4.8	-4.4	-2.0	6.2
	Annual total =	111.3	117.3	125.2	141.2	170.2
240	F 72	48.0	48.5	49.2	51.7	59.3
	W 96	77.9	80.6	83.8	87.9	91.1
	Sp 48	17.5	20.0	23.6	30.6	40.6
	S 24	-2.1	-1.8	-1.4	1.0	9.2
	Annual total =	141.3	147.3	155.2	171.2	200.2

[1]Negative numbers indicate water deficits.
[2]F, fall; W, winter; Sp, spring; S, summer.
[3]LAI = leaf area index.

Table 4—*Amount of water available for annual runoff, calculated by WATBAL as function of average annual precipitation, the percentage of original stand basal area remaining after fire, and aspect*

Aspect[1]	Average annual precipitation (cm)	Water available for annual runoff (cm) by percentage of original basal area				
		100 pct	50 pct	35 pct	10 pct	0
S	60	17.4	16.7	16.0	26.5	33.2
	90	39.9	39.2	38.5	50.8	58.9
	120	62.4	61.7	61.0	75.2	84.6
	150	86.4	85.7	85.0	101.4	111.6
	180	114.8	114.1	113.4	129.6	140.2
	210	144.8	144.1	143.4	159.6	170.2
	240	174.8	174.1	173.4	189.6	200.2
E/W	60	23.2	22.5	21.8	29.6	34.9
	90	47.1	46.4	45.7	54.5	60.4
	120	72.5	71.8	71.1	80.5	87.1
	150	99.9	99.2	98.5	108.2	115.0
	180	128.9	128.2	127.5	137.3	144.1
	210	158.9	158.2	157.5	167.3	174.1
	240	188.9	188.2	187.5	197.3	204.1
N	60	27.9	27.2	26.5	32.5	36.6
	90	53.0	52.3	51.6	58.0	62.4
	120	79.9	79.2	78.5	85.1	89.7
	150	109.2	108.5	107.8	114.6	119.4
	180	139.2	138.5	137.8	144.6	149.4
	210	169.2	168.5	167.8	174.6	179.4
	240	199.2	198.5	197.8	204.6	209.4

[1]S, South; E/W, East and West; N, North.

zone that receives an annual average precipitation of 120 cm. PROSPER predicts 21.4 cm of annual runoff (*fig. 3*), whereas WATBAL predicts 72.5 cm of annual runoff (*fig. 5*—east and west aspects chosen to represent an average effect of aspect). When all vegetation is removed from this hypothetical watershed, predicted water yields are 80.2 and 87.1 cm, respectively, and that difference is probably unimportant.

Estimated changes in annual runoff associated with partial removal of vegetation by fire, therefore, depend heavily on the model selected. Whether rain or snow dominates the hydrologic regime of a particular site, we strongly recommend consulting with a hydrologist or watershed specialist familiar with the hydrologic character of the area.

Figures 7 and *8*, respectively, present estimated changes in annual runoff as a function of annual precipitation and leaf area index reduction for rain-dominated hydrologic regimes and as a function of annual precipitation and aspect for sites with 100 percent basal area reduction in a snow-dominated regime.

The tables and figures presented in this paper provide a means of estimating postfire changes in water yield from forested watersheds in the Pacific Northwest. These estimates can be calculated for specific sites or for "generic" watersheds defined by precipitation class, aspect, and vegetation. Estimating for "generic" watersheds is particularly useful in fire management planning because long-term estimates are needed at a broad level of resolution.

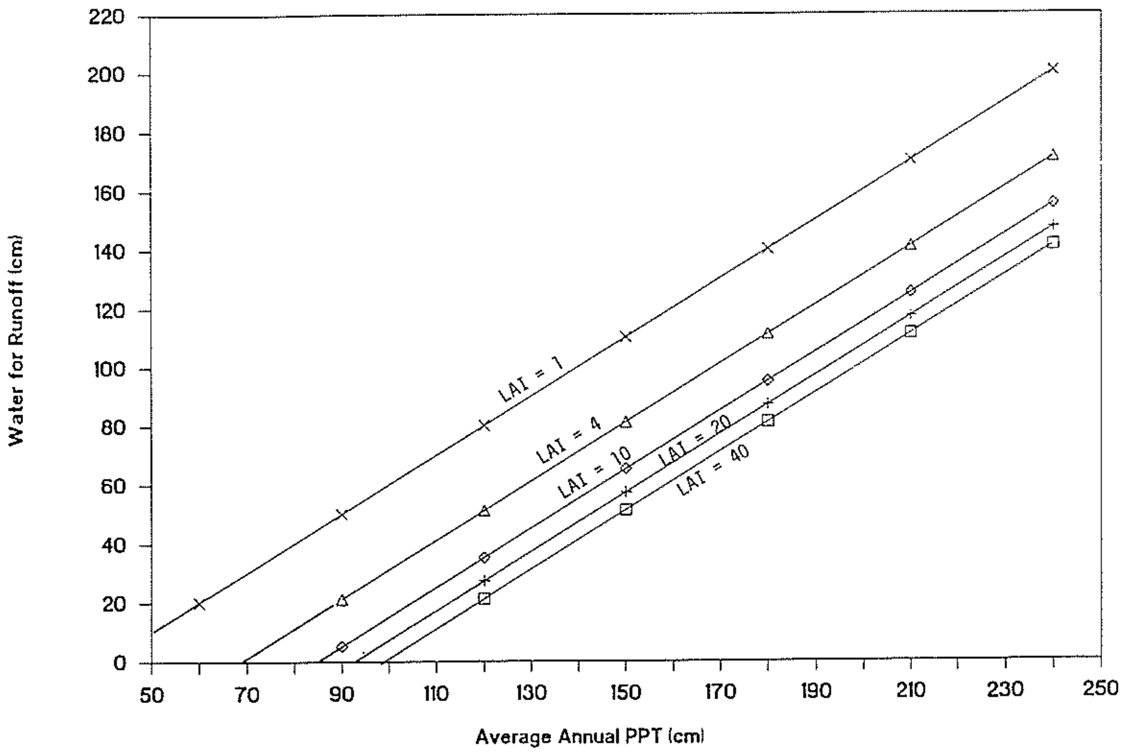

Figure 3—The WRENSS version of PROSPER estimates annually available water for runoff as a function of average annual precipitation (PPT) and leaf area index (LAI).

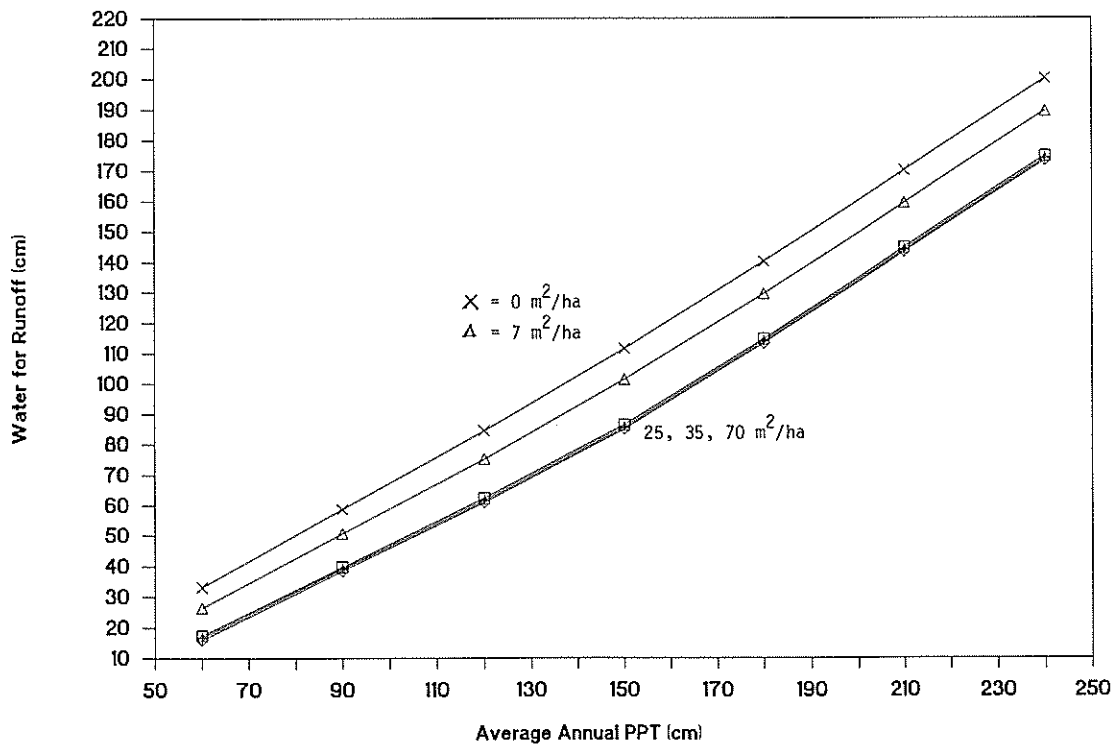

Figure 4—The WRENSS version of the snow model WATBAL estimates annually available water for runoff as a function of average annual precipitation (PPT) and basal area. Estimates are presented for the south energy aspect.

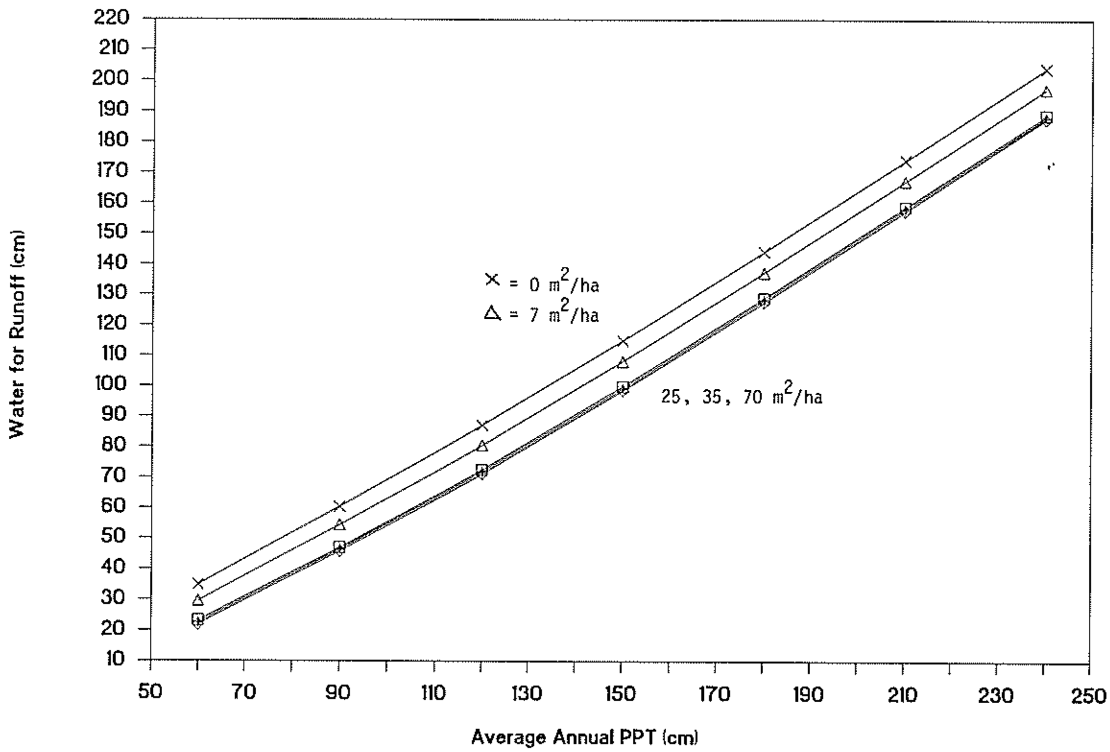

Figure 5—The WRENSS version of WATBAL estimates annually available water for runoff as a function of average annual precipitation (PPT) and basal area. Estimates are presented for the east and west energy aspects.

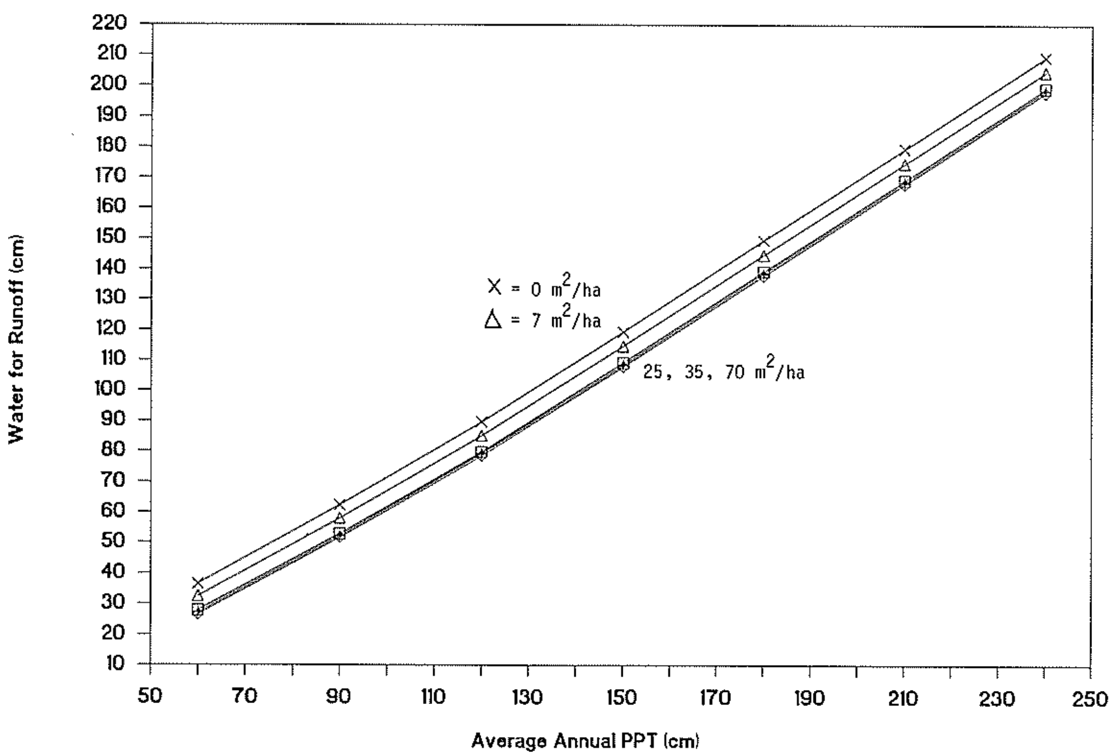

Figure 6—The WRENSS version of WATBAL estimates annually available water for runoff as a function of average annual precipitation and basal area. Estimates are presented for the north energy aspect.

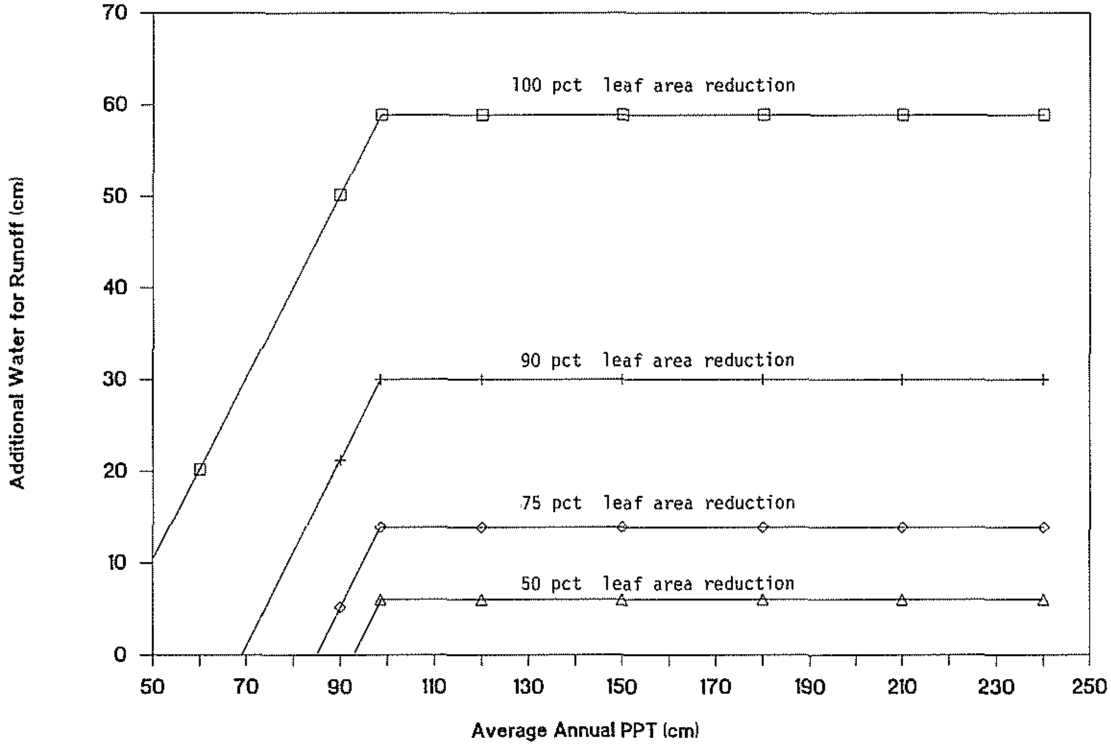

Figure 7—Estimated changes in annual runoff can be calculated as a function of annual precipitation and leaf area reduction in rain-dominated hydrologic regimes.

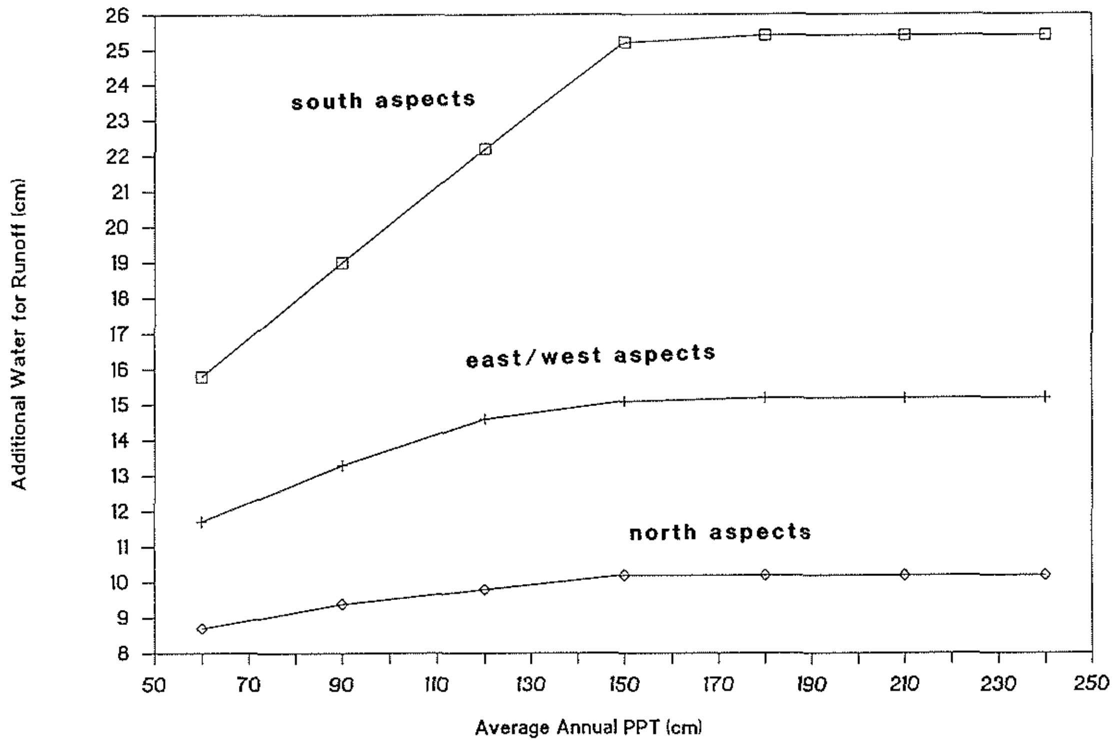

Figure 8—Estimated changes in annual runoff with 100 percent basal area reduction can be calculated as a function of annual precipitation and energy aspect in snow-dominated hydrologic regimes.

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