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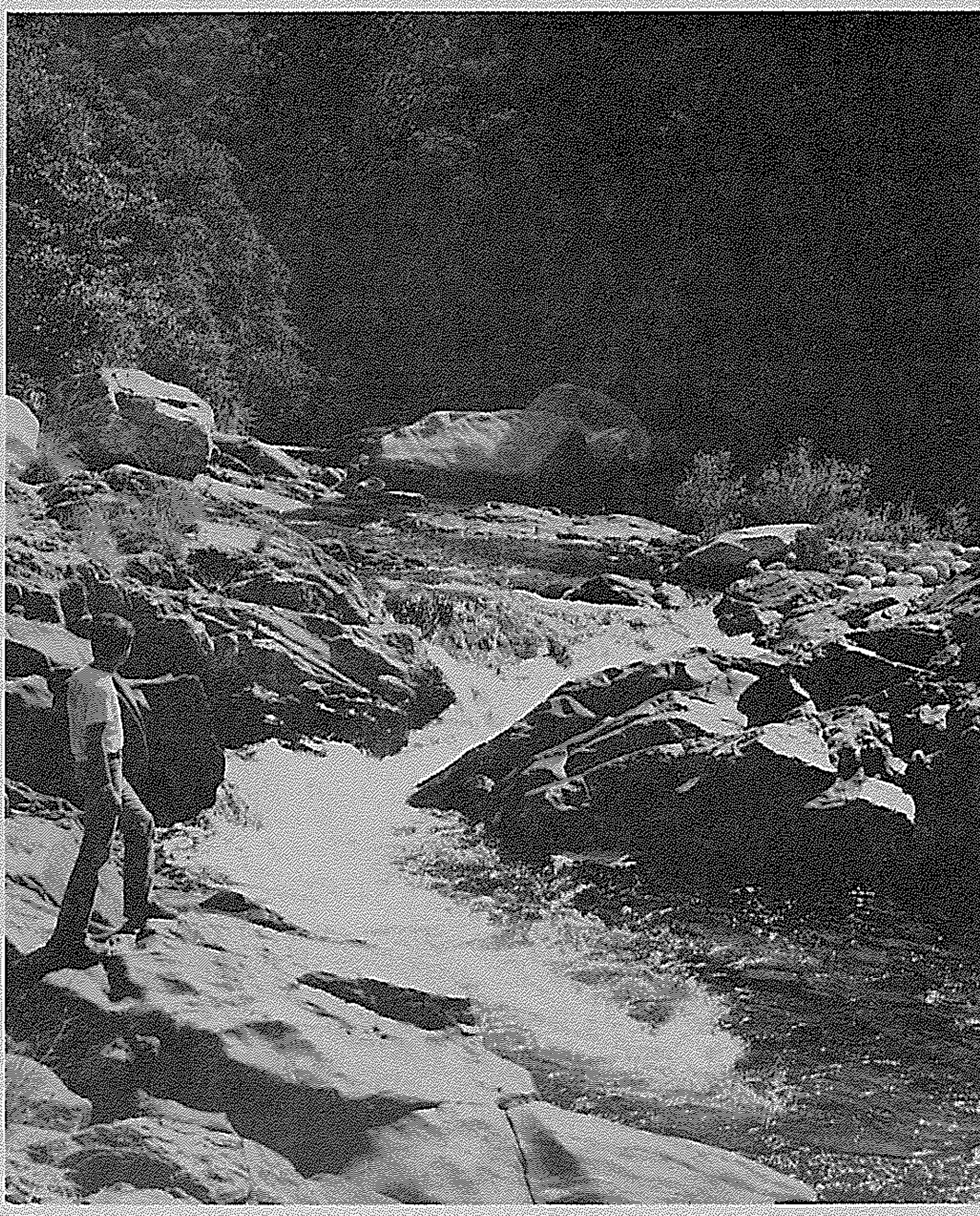
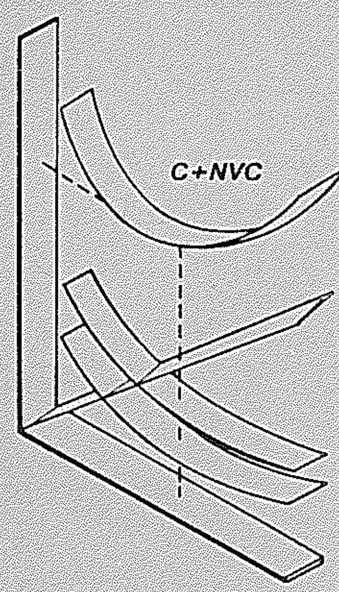
Watershed Modeling for Fire Management Planning in the Northern Rocky Mountains

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





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IN BRIEF...

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Water yield and sediment production almost always increase after wildfire has destroyed vegetative cover. The value of water generally is not as much appreciated in the water-rich northern Rocky Mountains as it is elsewhere. Increased water yield becomes economically beneficial, however, when its potential for consumptive and nonconsumptive uses is realized. Whether the effects of increased sedimentation are esthetic, biological, physical, or economic, they are usually detrimental.

Fire management programs for the National Forests are required to be an integral part of land management planning. Managers must be able to estimate postfire changes in resource outputs and values within the context of a particular fire management program. The quantity of additional water and sediment produced is a function of fire characteristics and site-specific factors: vegetation, climate, and physical characteristics. Planning, however, requires a broad resolution analysis system. Therefore, site-specific water and sediment yield models were adapted to meet broad resolution planning objectives.

In a study of fire-induced changes in watersheds in the northern Rocky Mountains, two simulation models were applied. Procedures from Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENSS) estimated water yield, and a closely related model estimated four major components of sediment yield—natural sediment, sediment from management-induced mass erosion, sediment from management-induced surface erosion, and sediment delivery. Computerized versions of the models were used to estimate postfire water yield for 18 possible management cases and postfire sediment yield for 81 cases. Net value change of water resources was calculated with investment analysis.

Water yield was most affected by basal area loss; the greater the loss, the greater the relative increase in water yield. Water yield increased over natural yield, however, only if fire or salvage logging or both removed greater than 50 percent of stand basal area.

Fire had a relatively small effect on sediment production in most cases. Increases were relatively large only for fires with large areas. Natural sediment yield increased more than did management-induced sediment yield. Postfire sediment increases were severe only on sites with steep slopes and large fires.

Increased water yields resulted in a beneficial net value change for all cases. Benefits were substantial (up to $33.42 per acre or $80.21 per hectare) in some cases and were less than $5 per acre ($12 per hectare) only in some cases with 50 percent basal area loss. Net value change was increasingly negative as basal area loss increased. Net value change for sediment yield was detrimental for all cases, but was always less than $.01 per acre ($.02 per hectare).

INTRODUCTION

Wildfire on forested watersheds in the northern Rocky Mountains increases both water yield and sediment production. Increased water yield is beneficial, but increased sedimentation is detrimental. Fire management programs for National Forest lands are required to be an integral part of land management plans and to be cost-effective (Nelson 1979; U.S. Dep. Agric., Forest Serv. 1979). In selecting a particular fire management program, a manager must be able to estimate accurately long-term changes in water resource outputs and values caused by wildfire.

Site-specific information about effects of fire is available for some ecosystems in the northern Rocky Mountains (Tiedemann and others 1979). For land management, however, the planning system must go beyond procedures based on site-specific information—it must be a broad resolution analysis system capable of estimating and analyzing changes caused by fire (Mills and Bratten 1982).

Fire produces both onsite and downstream effects on water resources. These different effects are impossible to separate, making broad resolution modeling difficult. However, some responses of water resources to fire are common or nonsite-specific (Tiedemann and others 1979, p. 23):

1. Fire exerts pronounced effects on basic hydrologic processes leading to increased sensitivity of the landscape to eroding forces and to reduced land stability. This is manifested primarily as increased overland flow, and greater peak and total discharge. These provide the transport force for sediment from the landscape.
2. Erosion responses to burning are a function of several factors including: degree of elimination of protective cover; steepness of slopes; degree of soil nonwettability; climatic characteristics; and rapidity of vegetation recovery.
3. Sedimentation, increased turbidity levels, and mass erosion appear to be the most serious threats to water resources after fire (especially wildfire). Elimination of protective streambank cover has been shown to cause temperature increases that might pose a threat to aquatic life.
4. Despite the lack of documentation of fire size and intensity, large fires of high intensity appear to have the greatest potential for causing damage to water resources.

Many hydrologic models exist, each with unique features associated with the objectives for which it was developed. Available methodologies have many limitations in meeting the objectives of fire management planning. Sediment and water yield models that are used most often are deterministic and site-specific. Probabilistic water yield modeling is limited by dependence on historical records for generating probability distributions. Stochastic models assume time-invariance of hydrologic systems. Probabilistic sediment yield models for large areas are nonexistent.

Because no combination of existing watershed models provides exactly what is required for fire management planning, we adapted the Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENSS) water yield model (U.S. Dep. Agric., Forest Serv. 1980) and a closely related sediment yield model (Cline and others 1981). These models are usually applied to site-specific situations, but are easily simplified and generalized. The modified models produce realistic estimates of changes in resource outputs at the level of resolution required for fire management planning. An investment analysis procedure is used to calculate the net value change of water resource outputs. These estimates may also be useful for quantifying change in production and value of resources for postfire impact assessment and escaped fire situation analyses.

This paper describes the use of site-specific water and sediment yield models to produce broad resolution estimates of expected changes in the northern Rocky Mountains due to fire. It describes model inputs and expected changes in resource outputs in terms of analysis units that represent various classes of watersheds, fire characteristics, and management options.

METHODS

Analysis Units

Numerous specific data are needed to estimate changes in postfire water yield and sediment production. Some of these inputs are general and others specific. Because estimates will be used in a planning context, a list of descriptors is needed that identifies nonsite-specific management situations at a broad level of resolution, and is compatible with the data. Therefore, we proposed a list of parameters that describe possible management

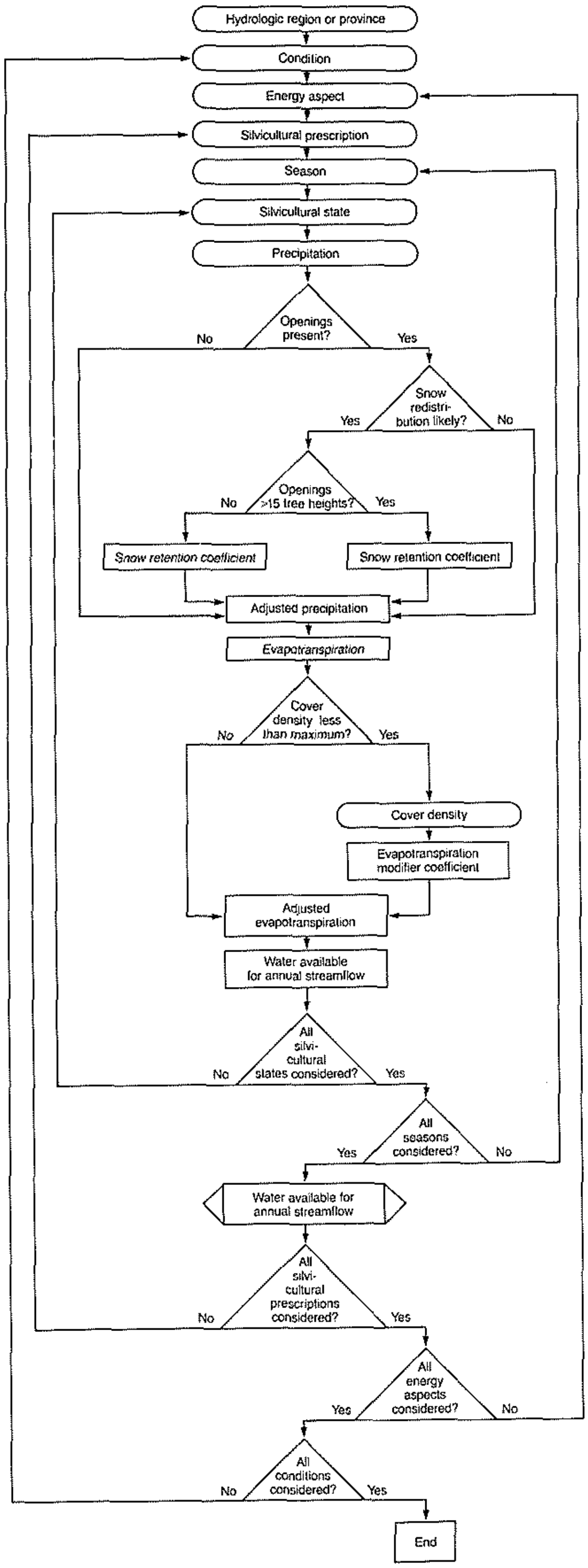

Figure 1—WATBAL is a complex model that simulates water available for streamflow in snow-dominated hydrologic regimes. Snow retention coefficients are from WRENSS documentation (U.S. Dep. Agric., Forest Serv. 1980).

cases or *analysis units* in terms of watershed characteristics, fire damage, and management decisions:

Parameter	Class
Slope, percent	20
	60
	90
Aspect	North
	South
	East, west
Cover type	Douglas-fir
	Ponderosa pine
	Western white pine
	Fir-spruce
	Hemlock-Sitka spruce
	Larch
	Lodgepole pine
Cover type age class	Sawtimber
	Pole
	Seedling/sapling
Annual precipitation, inches (cm)	15 (38)
	30 (76)
	45 (114)
Fire size, acres (ha)	30 (12)
	380 (154)
	2800 (1133)
Basal area loss, percent	20
	50
	90
	100
Roads	Present
	Absent
Salvage logging	Yes
	No

Three slope classes describe gentle, moderate, and steep slopes, because the models require a specific value for each class. Three aspect classes are used: north aspects have low evapotranspiration rates, south aspects have high rates, and east and west aspects are combined because they have similar intermediate rates. The seven major timber cover types identified in the northern Rocky Mountains are used in the model (Garrison and others 1977; U.S. Dep. Agric., Forest Serv. 1967). The cover type age class system is that used by the Forest Service. Precipitation is an input parameter because of its importance in determining water yield. Annual precipitation varies considerably by elevation and latitude in the northern Rocky Mountains, and can be correlated with these two factors in the context of land management planning. Values chosen for classes of annual precipitation generally are representative of precipitation received at 3000, 4500, and 6000 feet (910, 1360, and 1820 m) elevation in the northern Rocky Mountains. The values that represent three fire size classes are means within the fire size classes 0–99, 100–999, and 1000+ acres (0–41, 42–416, and 417+ ha) for the northern Rocky Mountains during 1970 to 1981 (Bratten 1983). Roads and salvage logging can affect the quantity of postfire sediment production; assumptions related to the effect of road density and salvage logging are discussed in the section on sediment yield. The many other assumptions and decision rules required in the watershed models are discussed in the following sections on the water yield and sediment yield models.

Water Yield Model

WRENSS (U.S Dep. Agric., Forest Serv. 1980) procedures use two different computer models: PROSPER in rain-dominated hydrologic regimes (below 4000 feet in the northern Rocky Mountains) (Goldstein and others 1974); and WATBAL in snow-dominated regimes (Leaf and Brink 1973a, 1973b). Because PROSPER has not been used extensively or validated in the northern Rocky Mountains, we used procedures from WATBAL only.

WATBAL was intended to be a site-specific model, but geographic regional coefficients and modifiers "will yield reasonable results which are applicable in the respective regions" (U.S. Dep. Agric., Forest Serv. 1980, p. III. 26). The following conventions and definitions were assumed for WATBAL (*fig. 1*):

Condition and silvicultural state—The model first estimates existing water yield from the burned area. All analysis units are assumed to be previously undisturbed and exhibit complete hydrologic utilization.

Energy aspect—Primary aspects considered are north, south, and east-west. While evapotranspiration rates are usually higher on west aspects than on east aspects because of greater afternoon vapor pressure deficits, the potential shortwave radiation loads are the same. These primary aspects are the same as the analysis unit classes listed on page 2.

Silvicultural prescription—Each fire size is assumed to represent a uniform subwatershed. Changes in water yield are determined for only the disturbed area. Analysis unit basal area loss and salvage decision rules define the silvicultural prescription.

Season—Three predisturbance and postdisturbance hydrologic seasons are used to estimate seasonal evapotranspiration and runoff: winter (October 1–February 28), spring (March 1–June 30), and summer-fall (July 1–September 30).

Precipitation—Only two of the analysis unit precipitation classes are used in the water yield analysis (30 and 45 inches). A generalized monthly distribution of total annual precipitation in the northern Rockies was used to form the seasons described above. With this distribution, even total vegetation removal would not produce significant surplus water for runoff unless annual precipitation was greater than about 20 inches (508 mm). WATBAL assumes that large openings are absent in undisturbed stands, and that snow received in the northern Rockies—particularly west of the Continental Divide—is unlikely to undergo significant redistribution when disturbance creates openings in a stand. Precipitation is not adjusted in either case.

Evapotranspiration—Seasonal evapotranspiration is determined from seasonal precipitation using the regional relationships provided in WRENSS.

Cover density and evapotranspiration modifier coefficients—Cover density is defined by an index that references the capability of the stand to use energy input for evapotranspiration. This capability varies as a function of crown closure, vertical foliage distribution, species, and stocking. WATBAL assumes that existing cover density in the undisturbed state is maximum cover density, and that hydrologic utilization is complete. Basal area loss in each analysis unit is related to residual cover density using regional relationships provided in WRENSS. The ratio of residual cover density to maximum cover density by season, elevation, and aspect determines the evapotranspiration modifier coefficient using regional relationships provided in WRENSS. Adjusted seasonal evapotranspiration is subtracted from seasonal precipitation to determine the seasonal water available for streamflow. Seasonal increases or decreases are summed to provide the estimate of net water yield change from the disturbed area after fire. WATBAL assumes that hydrologic recovery, that is, return to complete hydrologic utilization, occurs exponentially with time over a 25-year period.

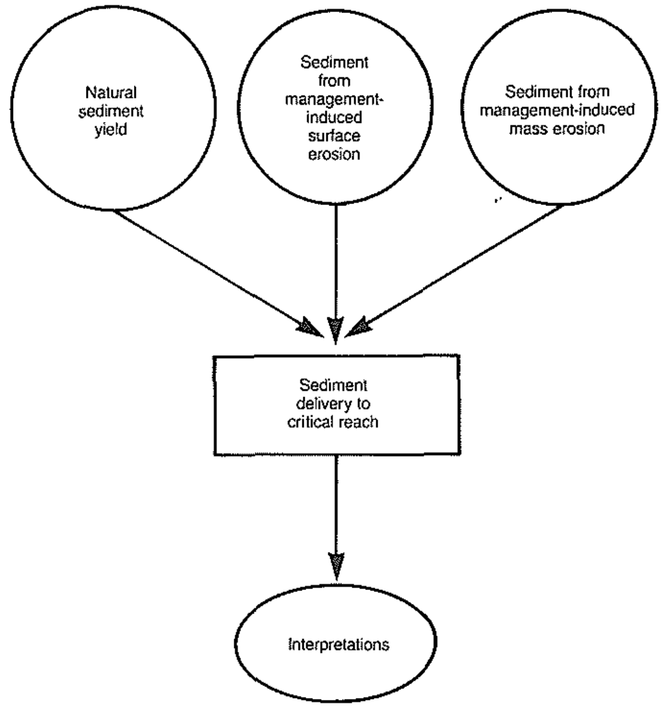

Figure 2—Sediment yield at a critical reach of a stream has several components.

Sediment Yield Model

The sediment yield model used in Forest Service's Northern (R-1) and Intermountain (R-4) Regions (Cline and others 1981, p. 1) is a "conceptual framework which outlines a process and is designed to be supplemented by local data. . . . " Its limitations and assumptions are clearly documented. At its current state of validation, the model can be used as a planning tool to compare land management alternatives.

The sediment yield model estimates four major components: (1) natural sediment yield, (2) sediment from management-induced mass erosion, (3) sediment from management-induced surface erosion, and (4) sediment delivery (*fig. 2*).

Natural Sediment Yield

The sediment yield model allows the user to supply estimates of natural sediment yield, if available. An alternative procedure empirically relates natural sediment yield to a calculated Mass Erosion Hazard Rating (MEHR) (U.S. Dep. Agric., Forest Serv.

1980, ch. 5). The procedure assumes that the predominant mass erosion hazard in the northern Rocky Mountains is from debris avalanche and debris flow failures.

Seven weighting factors, each with three classes, are used to determine the MEHR for each analysis unit. In order of decreasing importance, the factors are these: slope; precipitation; and—all least important—soil depth, subsurface drainage, soil texture, bedding structure, and slope configuration. MEHR slope weighting factor classes are the same as the analysis unit slope classes, and MEHR precipitation weighting factor classes are the same as the analysis unit precipitation classes. The least important MEHR weighting factors tend to require the most site-specific information. Because the analysis units do not provide this information, all were given medium class weights. Therefore, a total of nine MEHRs was required to characterize natural sediment yield in the given analysis units (three slope classes by three precipitation classes).

Sediment From Management-Induced Mass Erosion

WRENSS also provides a Management Induced Mass Erosion Hazard Rating (MIMEHR) system (U.S. Dep. Agric., Forest Serv. 1980, ch. 5). The sediment produced from management-induced mass erosion is difficult to quantify. As an approximation, we simply added the numerical MIMEHR and MEHR values, and determined the incremental sediment increase predicted from the empirical MEHR-natural sediment yield relationship given in the sediment yield model (Cline and others 1981).

Three weighting factors, each with three classes, are used to determine the management-induced hazard of debris avalanche and debris flow failures. In order of importance, these factors are (1) roads and skidways, (2) vegetative cover removal, and (3) harvest systems. The weight of each of these factors is influenced by slope, specific management practices, and the roading-salvage decisions made for each analysis unit. For example, slope greatly influences impacts of high density roading in disturbed areas. Vegetative cover removal is determined by fire intensity and salvage decisions for a given analysis unit. Slope limits specific harvest systems if salvage logging takes place. System assumptions concerning road density, fire intensity, and salvage logging methods are discussed in the next section.

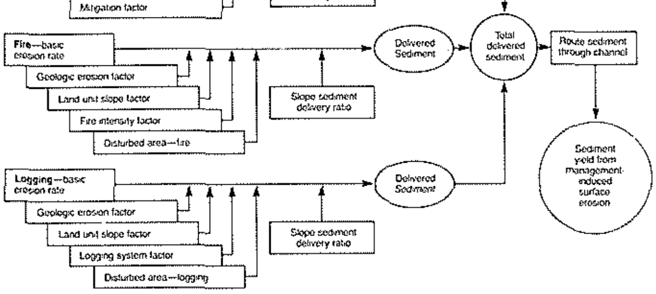

Figure 3—Management-induced surface erosion is a function of erosion caused by roads, fire, and logging.

Table 1—*Basic erosion rates (tons/mi²/yr) for three management practices over time, Idaho Batholith*

Practice	Year 1	2	3	4	5	6	>6
Roads[1]	67,500	18,000	5,000	5,000	5,000	5,000	5,000
Fire[2]	550	120	25	5	[3]0	0	0
Logging[4]	340	180	140	90	40	20	0

[1]Roads include horizontal distance from toe of fill to top of cut. Standard 16-foot road is assumed to have sustained 5–7 percent grade, balanced construction, inslope with ditch, native surface, and cross drains at 500-foot spacing. Standard road is constructed in granitic materials on a 50 percent side slope and is maintained annually.

[2]Standard fire is assumed to have burned at high intensity and consumed at least 40 percent of standing vegetation. Side slope is assumed to be approximately 45 percent.

[3]A zero indicates that erosion is not increased by a management practice at the given point in time.

[4]Standard logging system is clearcut with tractor yarding. Temporary roads and skid trails are assumed to be cross ditched and seeded as part of standard logging practice.

Sediment From Management-Induced Surface Erosion

The sediment yield model considers surface erosion and sediment production resulting from roads, fire, and logging (*fig. 3*) (Cline and others 1981). The surface erosion component was designed primarily from research conducted on granitic soils on the Idaho Batholith. Basic erosion rates are associated with standard management practices (*table 1*).

Basic erosion rates were modified with a geologic erosion factor for miscellaneous hard metamorphic rocks (Cline and others 1981). This linear multiplier is about 0.4. In other words, we assumed that basic erosion rates are 40 percent of the rates on granitic soil. Conversely, our sediment yield estimates can be modified for granitic soils with a multiplication factor of 2.5.

Additional assumptions of the sediment production model are these (*fig. 3*):

Disturbed area, road—Road density is 1 mi/mi^2 (0.6 km/km^2) in areas undisturbed by fire. In disturbed areas, road density is 2 mi/mi^2 (1.2 km/km^2). Analysis unit watersheds are 4.5 mi^2 (11.7 km^2); this assumption is discussed in the section on sediment delivery. The analysis unit fire size class determines the total length of road in a disturbed area; the remaining undisturbed area provides the additional road length. The total road disturbance width (toe of fill to top of cut) is 50 ft (15 m).

Mitigation factor, road—A number of vegetative and physical mitigation measures for road construction have erosion reduction percentages associated with them (Cline and others 1981). The maximum allowable reduction of the basic road erosion rates is 80 percent. We assume 80 percent reduction through a combination of seed and fertilizer application, and partial road closure (no maintenance).

Land unit slope factor, fire and logging—After fire or logging, erosion rates increase more on steeper slopes than they do on gentler slopes. Standard side slope is 45 percent. The land unit slope factor increases or decreases the basic erosion rates proportionally by the amount they deviate from the 45 percent slope.

The analysis unit slope classes produce adjustment factors of 0.6 (20 pct slope), 1.5 (60 pct) and 2.6 (90 pct).

Fire intensity factor—All fires burn with medium intensity: soil surface litter and humus are destroyed on up to 40 percent of the area, and the A horizon is heated intensely (Cline and others 1981). The fire intensity factor is 0.5, in other words, the basic erosion rate for the standard fire is reduced by one half.

Disturbed area, fire and logging—The analysis unit fire size classes determine the area disturbed by fire. If the salvage decision is made, then the same area is disturbed by logging.

Logging system factor—If timber is salvaged on an analysis unit, the disturbed area is clearcut. For the 20 percent slope class, the standard tractor logging system is used (factor = 1.0). For the two steeper slope classes (60 and 90 pct), a cable logging system is used (factor = 0.62).

Sediment Delivery

Not all material detached during surface erosion is transported to stream channels. The amount that reaches the stream channel divided by the amount that was originally detached is called the sediment delivery ratio. Sediment delivery is a complex process and the sediment yield model uses the WRENSS systematic technique for estimating delivery efficiency (U.S. Dep. Agric., Forest Serv. 1980, ch. 4).

The estimation procedure determines the relative area of a polygon formed as a function of eight land characteristics and applies this proportion to a conversion curve to determine sediment delivery for a slope class (*fig. 4*). The land characteristics are all site-specific, but the model assumptions place all analysis units into one of three sediment delivery classes on the basis of original analysis unit slope classes.

Not all material delivered to a stream channel is transported out of a watershed. Efficiency of channel delivery is a function of the drainage area (Cline and others 1981). The model assumes that the analysis unit watersheds (4.5 mi^2 or 11.7 km^2) have a routing coefficient of about 0.75.

Economic Analysis

The value of water resources after fire was determined by subtracting present net value of the resource with fire from present net value without fire:

$$NVC = PNV_{w/o} - PNV_{w} \qquad (1)$$

where

NVC = net value change per acre burned

$PNV_{w/o}$ = present net value of all future revenues in the "without-fire" situation

PNV_{w} = present net value of all future revenues in the "with-fire" situation

The general form of equation 1 can be expanded to its computational form:

$$NVC = \sum_{n=0}^{y} \frac{PQ_{w/o,\,n}}{(1 + i)^n} - \sum_{n=0}^{y} \frac{PQ_{w,\,n}}{(1 + i)^n} \qquad (2)$$

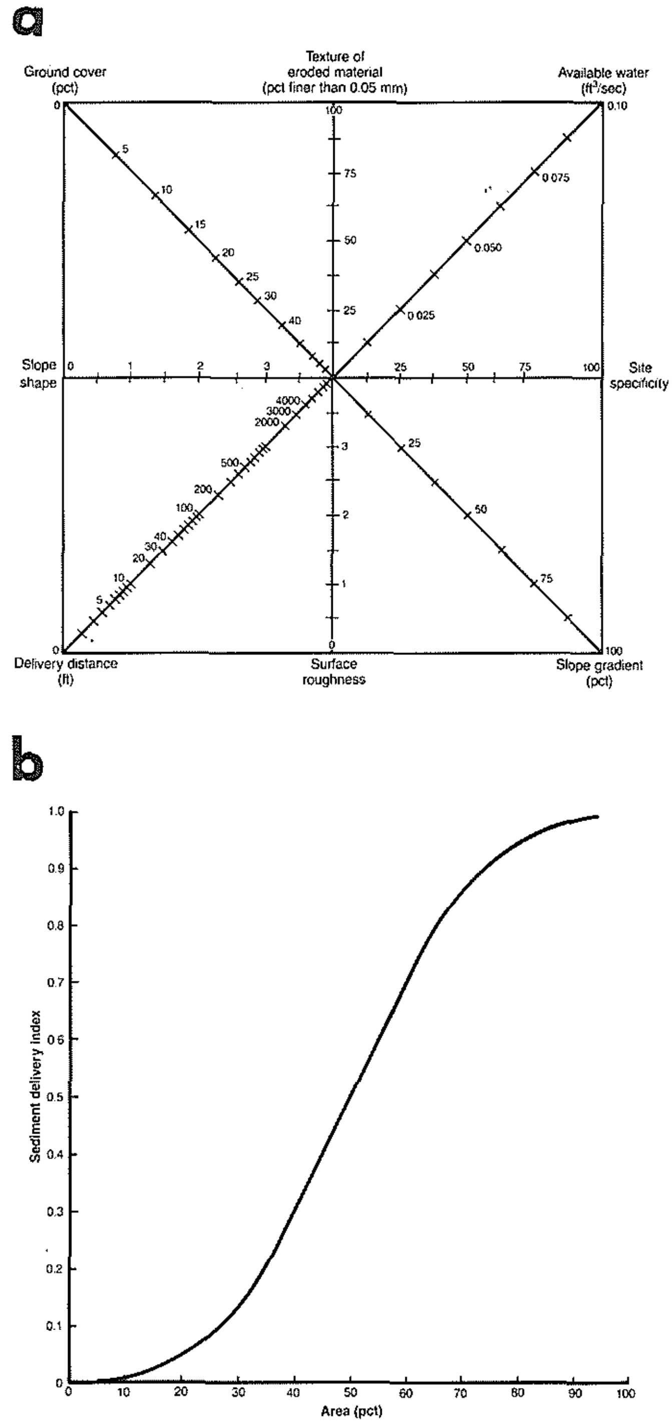

Figure 4—Relative areas of eight land characteristics that make up a polygon (a) are applied to a conversion curve (b) to determine the sediment delivery index. This index is used to calculate the quantity of detached material that reaches a stream channel. Slope shape is a dimensionless variable where 0 = concave, 4 = convex. Surface roughness is a dimensionless variable where 0 = smooth, 4 = rough. Site specificity is a dimensionless variable that expresses relative site specificity of a given analysis unit. Variables are discussed in greater detail in the WRENSS documentation (U.S. Dep. Agric., Forest Serv. 1980).

where

P = per unit value (of water or sediment), measured in 1982 dollars

$Q_{w/o,n}$ = yield (of water or sediment) per acre without fire in year n

$Q_{w,n}$ = yield (of water or sediment) per acre with fire in year n

i = discount rate

n = year of transaction

y = number of years in postfire time stream.

We assumed that differences in management costs between with-fire and without-fire regimes are negligible, and that all physical effects of fire are negligible beyond 25 years for water yield and 5 years for sediment yield. Discount rates of 4 and 10 percent were used in this analysis. The USDA Forest Service currently uses a 4 percent rate in land management planning, and the federal Office of Management and Budget (1972) recommends a 10 percent rate. Net value change was calculated with SASSY, an investment analysis computer package (Goforth and Mills 1975). SASSY performs the calculation in equation 2, given the following inputs: the timing or investment year of with-fire and without-fire water or sediment yields, the yield amount (acre-ft/acre for water, tons/mi^2 for sediment), price per unit, and discount rate.

The per-unit value of water was based on the value calculated for Forest Service Region 1 in the 1985 draft Resources Planning Act (RPA) Program, $13.50 (1982 dollars) per acre-foot of added water yield. The value of water is assumed to be equal to the marginal utility of the last increment of water in the lowest value consumptive use, which is irrigation. Water is used for irrigation only after higher value needs are met. Water benefit values are those used in RPA (Frank and Beattie 1979). The marginal product of the water input was calculated from estimated agricultural production functions, but estimated value of return flow and reuse were not included (Frank and Beattie 1979). The use of RPA values for the valuation of water yield is currently mandated for land management planning on all National Forests.

Water values can be determined by using criteria other than the lowest value consumptive use, such as the value of added water for the production of electricity (Vaux and Pour-Sanaie 1983). Water yield values for nine National Forests in the Columbia River Basin were weighted by forest acreage to produce an average value for the basin. Values ranged from $8.58 to $53.68 per acre-ft, with a weighted average value of $31.84 (1980 dollars). Use of this average value obviously would produce much higher estimates of economic change in water yield than would the marginal value.

Water value can also be calculated as the sum of the values for multiple uses. For example, the same increment of water can be used for irrigation, hydroelectric power generation, and municipal consumption. In addition, the use of water for agriculture depends on whether water can be made available for irrigation at times when it is needed. Although water surpluses are normally greatest in spring, demand for irrigation is usually greatest in late summer. Availability throughout the year often depends on storage capacity in reservoirs. The value of water is closely related to the actual demand for its use; this demand may vary.

Several methods can be used to calculate water value. Although we used RPA water values, the net value changes can be adjusted with an appropriate multiplier if a different water yield value is used.

The best per-unit values available for sediment production are estimates from the 1985 draft RPA Program. Sediment effects were tied to the direct impact on other resources or facilities (e.g., reservoirs) through damages and opportunity costs. Several studies and reports from different areas in the northern Rocky Mountains were categorized and weighted by kinds of impacts and land area involved.

The RPA value of $7 per thousand tons for Forest Service Region 1 was used to calculate NVC in equation 2; only the increase in sediment caused by fire was included. An increase in sediment production after a postfire salvage logging operation was attributed to fire, but sediment production due to an existing road system was not.

RESULTS AND DISCUSSION

Estimates of Postfire Water Yield

We estimated postfire water yield for 18 analysis units (*table 2*) using the computerized version of WRENSS, WSDU*WATER.WET. Complete model documentation and sensitivity analysis are available (Williams and Daddow 1984).

Results are given for a Douglas-fir cover type. With the exception of lodgepole pine, all cover types yield similar evapotranspiration modifier coefficients for the three basal area loss classes; therefore, postfire water yield increases will be similar. If estimates for a lodgepole pine cover type are desired, reduce the water yield increases *(table 2)* by about 20 percent.

The general seasonal distribution of annual precipitation used in this analysis was 40 percent winter, 40 percent spring, and 20 percent summer-fall. Winter precipitation contributed most to total water yield (Williams and Daddow 1984). The assumed distribution should provide valid results for most of the northern Rocky Mountains.

Basal area loss was the most important analysis unit parameter that affected water yield because it determines postfire evapotranspiration of a forest stand. The greater the basal area loss, the greater was the relative increase in water yield *(table 2)*. Water yield increased over natural yield only if fire or salvage logging or both removed greater than 50 percent of stand basal area. Increasing basal area loss from 90 to 100 percent produced an incremental increase in water yield almost as large as the difference between water yield for 50 and 90 percent losses.

Table 2—*Estimated natural water yield, and total increases in water yield 1 and 25 years after fire, by analysis unit, northern Rocky Mountains*

Analysis unit	Analysis unit parameters: Annual precipitation	Aspect	Basal area loss	Water yield: Natural	1-year increase postfire		Total 25-year increase in water yield
	inches		*pct*	*acre-ft/acre*		*pct*	*acre-ft/acre*
1	30	North	50	1.420	0.015	1	0.126
2			90	1.420	0.140	10	1.250
3			100	1.420	0.267	19	2.241
4		East-west	50	1.218	0.047	4	0.393
5			90	1.218	0.143	12	1.204
6			100	1.218	0.247	20	2.073
7		South	50	0.986	0.087	9	0.729
8			90	0.986	0.187	19	1.365
9			100	0.986	0.287	29	2.409
10	45	North	50	2.497	0.045	2	0.378
11			90	2.497	0.212	8	1.781
12			100	2.497	0.372	15	3.075
13		East-west	50	2.296	0.053	2	0.450
14			90	2.296	0.170	7	1.428
15			100	2.296	0.292	13	2.456
16		South	50	2.104	0.097	5	0.821
17			90	2.104	0.217	10	1.822
18			100	2.104	0.327	16	2.746

The largest increase in water yield was calculated for analysis unit 12, a site with high precipitation, north aspect, and 100 percent of basal area removed *(table 2)*. Analysis units with high precipitation had higher water yields than did their low precipitation counterparts. Analysis units with north aspects had higher water yields than did units on south and east-west aspects for a given precipitation class and basal area loss.

Possible Adjustments

Annual precipitation in the northern Rocky Mountains varies with latitude and elevation. The water yield estimates (*table* 2) are generally representative of mid-elevation and higher elevation timber harvest zones. However, water yield estimates may be needed for other precipitation levels. The model estimates water yield increases that are nearly linear with precipitation increases above a minimum level of precipitation (Williams and Daddow 1984). Therefore, natural water yield estimates *(table 2)* may be adjusted by approximately 0.4 acre-ft per 5-inch precipitation increment.

Adjusting postfire increases in water yield to a different precipitation class is difficult due to nonlinear functions used in the model. However, increases in first-year postfire percentage are reasonably consistent in given aspect and basal area loss classes. Water yield increases for a different precipitation class can be approximated by simply multiplying an *adjusted* natural water yield by the appropriate (basal area loss and aspect class) percentage increase *(table 2)*.

Total 25-year water yield increases are determined by integrating an exponential function over a 25-year recovery period. A simple algorithm multiplies the first-year postfire increase by 8.0. *Adjusted* total 25-year water yield may be determined in a similar manner by multiplying *adjusted* first-year postfire increase by 8.0.

Total Yield Increases

The water yield estimates *(table 2)* are independent of fire size class. To estimate total water yield increases, multiply the water yields *(table 2)* by the fire size. We did *not* use the model to predict changes in peak discharge or the timing of peak discharge.

Estimates of Postfire Sediment Yield

We estimated sediment yield 1 year after fire for 81 analysis units (3 precipitation classes by 3 slope classes by 3 fire-size classes by 3 road-salvage decisions) with WATSIM, a computerized version of the sediment yield model (Zuuring and Potts, 1985) *(table 3)*.

Fire had a relatively small effect on sediment production in most analysis units. Only those analysis units with the largest fire size class had relatively large increases in sediment. Salvage logging had its greatest effect on the largest fire size class as well, but produced relatively small increases for all analysis units. Natural sediment yield was greater than management-induced sediment yield (fire plus roads plus logging) in 60 of the 81 analysis units *(table 3)*.

The largest absolute increase in sediment production was calculated for analysis unit 81, a roaded site with high precipitation, 90 percent slope, a 2800-acre fire, and salvage logging. The estimated sediment yield of 181.2 tons/mi^2/yr is still relatively small and decreases rapidly over time. The largest relative in-

Table 3—*Estimated sediment yield 1 year after fire by analysis unit, showing separate contributions from fire, roads, and salvage logging, northern Rocky Mountains*

Analysis unit	Analysis unit parameters					Sediment yield[1]						
	(1) Annual precipitation	(2) Slope	(3) Fire size	(4) Roads	(5) Salvage logging	(6) Natural	(7) Fire	(8) Roads	(9) Logging	(10) Management induced	(11) Total	(12) Increase over natural
	inches	*pct*	*acres*					*tons/mi²/yr*				*pct*
1	15	20	30	No	No	10.2	--	0	0	--	10.2	0
2				Yes	No	10.2	--	8.3	0	8.3	18.5	81
3				Yes	Yes	10.2	--	8.3	--	8.3	18.5	81
4			380	No	No	10.2	.6	0	0	.6	10.8	6
5				Yes	No	10.2	.6	8.3	0	8.9	19.1	87
6				Yes	Yes	10.2	.6	8.3	.6	9.5	19.7	93
7			2800	No	No	10.2	8.3	0	0	8.3	18.5	81
8				Yes	No	10.2	8.3	8.3	0	16.6	26.8	163
9				Yes	Yes	10.2	8.3	8.3	5.1	21.7	31.9	213
10		60	30	No	No	19.2	.6	0	0	.6	19.8	3
11				Yes	No	19.2	.6	12.8	0	13.4	32.6	70
12				Yes	Yes	19.2	.6	12.8	--	13.4	32.6	70
13			380	No	No	19.2	3.2	0	0	3.2	22.4	17
14				Yes	No	19.2	3.2	12.8	0	16.0	35.2	83
15				Yes	Yes	19.2	3.2	12.8	1.3	17.3	36.5	90
16			2800	No	No	19.2	30.7	0	0	30.7	49.9	160
17				Yes	No	19.2	30.7	12.8	0	43.5	62.7	227
18				Yes	Yes	19.2	30.7	12.8	11.5	55.0	74.2	286
19		90	30	No	No	48.6	.6	0	0	.6	49.2	1
20				Yes	No	48.6	.6	17.3	0	17.9	66.5	37
21				Yes	Yes	48.6	.6	17.3	--	17.9	66.5	37
22			380	No	No	48.6	8.3	0	0	8.3	56.9	17
23				Yes	No	48.6	8.3	17.3	0	25.6	74.2	53
24				Yes	Yes	48.6	8.3	17.3	1.3	26.9	75.5	55
25			2800	No	No	48.6	73.0	0	0	73.0	121.6	150
26				Yes	No	48.6	73.0	17.3	0	90.3	138.9	186
27				Yes	Yes	48.6	73.0	17.3	14.7	105.0	153.6	216
28	30	20	30	No	No	11.5	--	0	0	--	11.5	0
29				Yes	No	11.5	--	8.3	0	8.3	19.8	72
30				Yes	Yes	11.5	--	8.3	--	8.3	19.8	72
31			380	No	No	11.5	.6	0	0	.6	12.1	5
32				Yes	No	11.5	.6	8.3	0	8.9	20.4	77
33				Yes	Yes	11.5	.6	8.3	.6	9.5	21.0	83
34			2800	No	No	11.5	8.3	0	0	8.3	19.8	72
35				Yes	No	11.5	8.3	8.3	0	16.6	28.1	144
36				Yes	Yes	11.5	8.3	8.3	5.1	21.7	33.2	187
37		60	30	No	No	22.4	.6	0	0	.6	23.0	3
38				Yes	No	22.4	.6	12.8	0	13.4	35.8	60
39				Yes	Yes	22.4	.6	12.8	--	13.4	35.8	60
40			380	No	No	22.4	3.2	0	0	3.2	25.6	14

crease in sediment production over natural yield was calculated for analysis unit 18, a roaded site with low precipitation, 60 percent slope, a 2800-acre fire, and salvage logging.

Postfire sediment increases were severe only on sites with steep slopes and large fires. Resource managers and planners concerned with sediment production should be aware of this general trend. Management decisions can be based on absolute increases in sediment production, relative increases, or both. The criterion used may depend on which resources are emphasized within a watershed and the projected reliability of the absolute values.

Possible Adjustments

Changing one of the assumptions can significantly change some postfire sediment yield estimates *(table 3)*. However, the analysis unit watersheds are "simple" scenarios: each represents a single land-type unit, an area homogeneous in physical and vegetative characteristics. With the exception of standard road-erosion mitigation practices, assumptions like minimum delivery distances ensure high sediment yield estimates.

We assumed a miscellaneous metamorphic rock type for this analysis. This type is representative of one of four basic groups of rock types and the geologic erosion factors associated with

Table 3—*Estimated sediment yield 1 year after fire by analysis unit, showing separate contributions from fire, roads, and salvage logging, northern Rocky Mountains— continued*

Analysis unit	Analysis unit parameters					Sediment yield[1]						
	(1) Annual precipitation	(2) Slope	(3) Fire size	(4) Roads	(5) Salvage logging	(6) Natural	(7) Fire	(8) Roads	(9) Logging	(10) Management induced	(11) Total	(12) Increase over natural
	inches	*pct*	*acres*			*tons/mi²/yr*						*pct*
41				Yes	No	22.4	3.2	12.8	0	16.0	38.4	71
42				Yes	Yes	22.4	3.2	12.8	1.3	17.3	39.7	77
43			2800	No	No	22.4	30.7	0	0	30.7	53.1	137
44				Yes	No	22.4	30.7	12.8	0	43.5	65.9	194
45				Yes	Yes	22.4	30.7	12.8	11.5	55.0	77.4	246
46		90	30	No	No	53.8	.6	0	0	.6	54.4	1
47				Yes	No	53.8	.6	17.3	0	17.9	71.7	33
48				Yes	Yes	53.8	.6	17.3	--	17.9	71.7	33
49			380	No	No	53.8	8.3	0	0	8.3	62.1	15
50				Yes	No	53.8	8.3	17.3	0	25.6	79.4	48
51				Yes	Yes	53.8	8.3	17.3	1.3	26.9	80.7	50
52			2800	No	No	53.8	73.0	0	0	73.0	126.8	136
53				Yes	No	53.8	73.0	17.3	0	90.3	144.1	168
54				Yes	Yes	53.8	73.0	17.3	14.7	105.0	158.8	195
55	45	20	30	No	No	17.9	--	0	0	--	17.9	0
56				Yes	No	17.9	--	8.3	0	8.3	26.2	46
57				Yes	Yes	17.9	--	8.3	--	8.3	26.2	46
58			380	No	No	17.9	.6	0	0	.6	18.5	3
59				Yes	No	17.9	.6	8.3	0	8.9	26.8	50
60				Yes	Yes	17.9	.6	8.3	.6	9.5	27.4	53
61			2800	No	No	17.9	8.3	0	0	8.3	26.2	46
62				Yes	No	17.9	8.3	8.3	0	16.6	34.5	93
63				Yes	Yes	17.9	8.3	8.3	5.1	21.7	39.6	121
64		60	30	No	No	35.6	.6	0	0	.6	36.2	2
65				Yes	No	35.6	.6	12.8	0	13.4	49.0	38
66				Yes	Yes	35.6	.6	12.8	--	13.4	49.0	38
67			380	No	No	35.6	3.2	0	0	3.2	38.8	9
68				Yes	No	35.6	3.2	12.8	0	16.0	51.6	45
69				Yes	Yes	35.6	3.2	12.8	1.3	17.3	52.9	49
70			2800	No	No	35.6	30.7	0	0	30.7	66.3	86
71				Yes	No	35.6	30.7	12.8	0	43.5	79.1	122
72				Yes	Yes	35.6	30.7	12.8	11.5	55.0	90.6	154
73		90	30	No	No	76.2	.6	0	0	.6	76.8	1
74				Yes	No	76.2	.6	17.3	0	17.9	94.1	23
75				Yes	Yes	76.2	.6	17.3	--	17.9	94.1	23
76			380	No	No	76.2	8.3	0	0	8.3	84.5	11
77				Yes	No	76.2	8.3	17.3	0	25.6	101.8	33
78				Yes	Yes	76.2	8.3	17.3	1.3	26.9	103.1	35
79			2800	No	No	76.2	73.0	0	0	73.0	149.2	96
80				Yes	No	76.2	73.0	17.3	0	90.3	166.5	119
81				Yes	Yes	76.2	73.0	17.3	14.7	105.0	181.2	138

[1]-- = negligible.

them (Cline 1982). Simple multiplication can be used to adjust the management-induced sediment *(table 3)* for other rock types. To adjust the prediction to hard sedimentary rocks, multiply by 1.25; to soft sedimentary rock or schist, multiply by 1.75; to granitics, multiply by 2.5.

Total Yield Increases

Adding the *adjusted* management induced sediment to the natural sediment (column 10 plus column 6, *table 3*) provides an *adjusted* total (column 11) that would then provide an *adjusted* increase over natural sediment yield (column 12).

Net Value Change of Water Resources

Increased water yields resulted in a beneficial (negative) net value change for all analysis units *(table 4)*. Net value change was proportional to the physical change in water yield *(table 2)*. Benefits were substantial in some cases, and were less than $5 per acre only in some analysis units with 50 percent basal area loss. The largest increase in value was $33.42 per acre (at a 4 percent discount rate) for an analysis unit with high rainfall, north aspect, and 100 percent basal area loss. The most important trend was that net value change was increasingly negative as basal area

Table 4—*Net value change of postfire water yield by analysis unit, northern Rocky Mountains*

Analysis unit	Analysis unit parameters: Annual precipitation	Aspect	Basal area loss	Net value change[1]: 4 pct rate	10 pct rate
	inches		*pct*	*1982 dollars*	
1	30	North	50	−1.37	−1.05
2			90	−13.34	−10.27
3			100	−23.98	−18.49
4		East-west	50	−10.14	−4.84
5			90	−12.79	−9.88
6			100	−22.12	−17.06
7		South	50	−7.89	−6.07
8			90	−16.84	−12.97
9			100	−25.86	−19.93
10	45	North	50	−4.04	−3.12
11			90	−19.04	−14.68
12			100	−33.42	−25.76
13		East-west	50	−4.79	−3.70
14			90	−15.21	−11.74
15			100	−26.25	−20.23
16		South	50	−8.71	−6.71
17			90	−19.43	−14.99
18			100	−29.34	−22.62

[1]Negative net value change indicates an increase (benefit) in postfire water value.

loss increased *(table 4)*. The magnitude of the change in NVC between 50 and 90 percent basal area loss for a given precipitation class and aspect was similar to that between 90 and 100 percent basal area loss. Net value increased more than $20 per acre (at a 4 percent discount rate) for all analysis units with 100 percent basal area loss.

Net value change for sediment production was detrimental (positive) for all analysis units but was always less than $.01 per acre, because the per-unit value of sediment is so low ($7 per thousand tons). Net value changes for fire-caused sediment production are not included because of these extremely small value changes.

The economic impact of increased sediment production after fire is small, even if the fire is large and severe and includes salvage logging. Net value change caused by increased sediment is insignificant compared with that caused by increased water yield. Small increases in postfire sediment production may have some local impacts, such as temporary damage to fish habitat. Although this kind of damage is poorly quantified and difficult to assess with an economic analysis, minimization of damage to fish habitat by sediment may have a greater influence on management decisions in some cases than do economic criteria. Relative increases in sediment production *(table 3)* may be used to assist in these management decisions.

Fires that are severe enough to kill at least half of the basal area in a stand can cause substantial increases in water yield *(table 2)* and some relatively large beneficial net value changes *(table 4)*. A postfire management decision to remove additional timber in a salvage logging operation results in an even greater net value change. Increased water yield in areas used for commercial timber production can offset possible losses in the value of timber due to fire. Increased water yield in unroaded or wilderness areas can result in substantial economic benefits because no commercial timber is lost.

CONCLUSIONS

An analytical system can be used to estimate nonsite-specific postfire changes in water resource outputs at a broad level of resolution appropriate for planning. We used well-documented, state-of-the-art procedures to estimate these changes rather than develop a new untested system. Greater confidence in estimates can be obtained only with a case-by-case analysis. We have also indicated possible adjustments to our estimates that would permit a greater level of site specificity. The water and sediment yield models are both readily available and can be used directly if greater resolution is necessary.

Water yield increases after fire are affected greatly by the amount of basal area killed by fire and removed by salvage logging. This increase is greatest in the year immediately after fire and decreases exponentially during a 25-year postfire period. This increase can be up to 0.4 acre-ft/acre in the first year after fire and 3.1 acre-ft/acre for the 25-year period *(table 2)*.

Fire had a relatively small effect on sediment production, even if there was a postfire timber harvest. The increase in sediment was greatest in the year after the fire and decreased during a 5-year postfire period. Maximum sediment production in absolute terms was only 181 tons/mi^2/yr (428 tonnes/km^2/yr), although increase over natural yield was as high as 284 percent. The greatest increases in sediment yield were calculated for analysis units with steep slopes and large fires.

The economic benefits of increased water yield are directly proportional to the quantity of water produced. Although water is not valued as highly in the northern Rocky Mountains as it is in other regions of the country, estimated postfire net value change was as high as $33 per acre. This benefit of fire should be considered with benefits and losses for other resources in calculating total net value change for various fire management situations. Increased sediment production is detrimental but the predicted loss of net value is small. The net value change estimates in this paper allow resource managers to make decisions on the basis of economic criteria. Environmental impacts such as damage to fish habitat from sediment may outweigh economic considerations in some cases. Estimates of sediment production reported here can be used to make decisions based on physical output changes.

We recommend using estimates reported in this paper for planning and other broad resolution applications only. The estimates may have some value for postfire impact assessment and escaped fire situation analyses, but should be used cautiously for such site-specific purposes. Users should be aware of the basic structure and assumptions of the water and sediment yield models before applying these estimates to any management situation.

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Two simulation models were adapted to estimate postfire changes in water yield and sediment production in northern Rocky Mountain watersheds. Data on topography, vegetation, and climate were used to simulate expected changes in resource production and value after wildfire. Management decisions were incorporated into the simulation approach. The results suggest that water yield increases were most affected by the amount of basal area killed by fire and removed by salvage logging, that estimated postfire benefits due to increased water yield were substantial, and that losses due to increased sedimentation were negligible. This simulation approach can be useful to managers who need to estimate long-term changes in water yield and value caused by wildfire.

Retrieval Terms: fire effects, net value change, sediment, water yield, watershed models