Hydrologic and Erosional Responses of a Granitic Watershed to Helicopter Logging and Broadcast Burning

WALTER F. MEGAHAN
JOHN G. KING
KATHLEEN A. SEYEDBAGHERI

ABSTRACT. Forest land managers are concerned about the effects of logging and site preparation on erosion, site productivity, streamflow, and water quality. Effects of helicopter logging and prescribed burning on streamflow and sediment yields from headwater drainages in the Idaho Batholith were evaluated, using paired watersheds monitored from 1966 to 1986. In the fall of 1976, 23% of a 162 ha watershed was clearcut. All the cutting units were located on south-facing slopes. Helicopter logging was followed by broadcast burning on the cutting units. Streamflow parameters showed little change in response to the logging and burning. However, total annual sediment yields on the treated watershed increased an average of 97% in the 10 yr following logging, with the largest increases occurring in the years of highest sediment yields. Increased sediment yields did not appear to result from accelerated channel erosion; rather, about 94% was attributed to accelerated surface erosion on the cutting units, and 6% was contributed by a single mass erosion site. Accelerated erosion persisted on the cutting units throughout the study period. The accelerated surface erosion occurred primarily as a result of the prescribed burning (rather than the helicopter logging); surface erosion rates on the burned areas were about 66 times greater than those on undisturbed slopes. The accelerated rates of erosion and sedimentation have potentially serious implications for on-site productivity and downstream resources. FOR. SCI. 41(4):777–795.

ADDITIONAL KEY WORDS. Streamflow, sedimentation, surface erosion, mass erosion, site productivity.

FOREST LAND MANAGERS ARE CONCERNED ABOUT the effects of logging and site preparation on erosion, site productivity, streamflow, and water quality. On steep, sensitive landscapes, helicopter logging is often used to minimize site disturbance and surface erosion. A paired watershed study was conducted to evaluate the effects of helicopter logging and site preparation burning on streamflow and sediment yield. It was one of several studies conducted in the Silver Creek Study Area (Figure 1) to evaluate the environmental effects of various timber harvest, site preparation, and road construction practices.

The study area, like most of mountainous central Idaho, is in the 40,000 km^2 Idaho Batholith. Soils derived from these granitic rocks are cohesionless and highly erodible, averaging only about 15% silt and clay (Megahan 1975). At many locations, a combination of steep slopes, erodible soils, and relatively high climatic stress from summer convective rainstorms and rapid spring snowmelt runoff increases erosion potential following timber harvest. Consequently, downstream

Reprinted from *Forest Science*, Vol. 41, No. 4, November 1995

sedimentation and its effects on both resident and anadromous fish habitat are major concerns.

The potential for accelerated surface erosion is usually considered to be minimal when helicopter logging systems are used. Megahan (1981) summarized the results of 16 studies documenting the amount of soil disturbance caused by timber felling and skidding operations and construction of access roads in western forests of the United States. Helicopter logging caused the least soil disturbance of the logging systems tested, with an average total area of disturbance of 4%, compared to 9.1% for skyline, 23.9% for ground cable, and 33.5% for tractors. However, helicopter logging is the most expensive of all logging systems and is generally used only on sites where both erosion risks and timber values are high. It is often prescribed on the high-hazard lands in the Idaho Batholith.

Factors other than the type of logging system influence surface erosion in the Idaho Batholith. Additional postharvest soil disturbance may result from reforestation or slash disposal activities. Prescribed burning of logging debris, either in piles or broadcast over the cutting units, is a common practice to reduce wildfire hazards, prepare seedbeds, and suppress plant competition for regeneration.

Surface erosion can also vary by slope aspect. Based on simulated rainfall data, Bethlahmy (1967) reported significantly greater erosion ($P < 0.01$) on undisturbed south slopes than on undisturbed north slopes, because of lower vegetative cover densities on the south slopes. Logging using a suspended cable system caused increased erosion ($P < 0.05$) on south slopes only.

In this study, the cutting units were located on south slopes, where potential increases in surface erosion rates should be greatest based on the Bethlahmy (1967) study. Measurements of streamflow, sediment yield, and channel sediment storage, along with observations of on-site erosion processes, were used to evaluate responses for 10 yr following logging and burning.

STUDY AREA AND TREATMENT

The study area is located in the Silver Creek drainage, a tributary to the Middle Fork of the Payette River in Idaho (Figure 1) on the Boise National Forest. Several watersheds, representative of conditions in the southwestern part of the Idaho Batholith, were selected for inclusion in the Silver Creek Study Area based on similarities in hydrologic and topographic characteristics. The study watersheds numbered 3 (WSD3) and 6 (WSD6) were used for this study.

Annual precipitation on the study area averages about 1000 mm. Summers are hot and dry with only occasional localized convective storms. About 65% of the annual precipitation occurs as snowfall and maximum snowpack water equivalent averages about 530 mm. As a result, snowmelt dominates the annual hydrograph, with maximum streamflows occurring during the spring snowmelt months of March through May.

Bedrock on the study watersheds is primarily coarse-grained quartz monzonite and is typical of a large part of the central and southern portions of the Idaho Batholith (Ross 1963). Physiographic characteristics of these headwater catchments are representative of the midelevation fluvial landscapes of the Idaho Batholith, with steep slopes and V-shaped valleys (Table 1). Soils are weakly

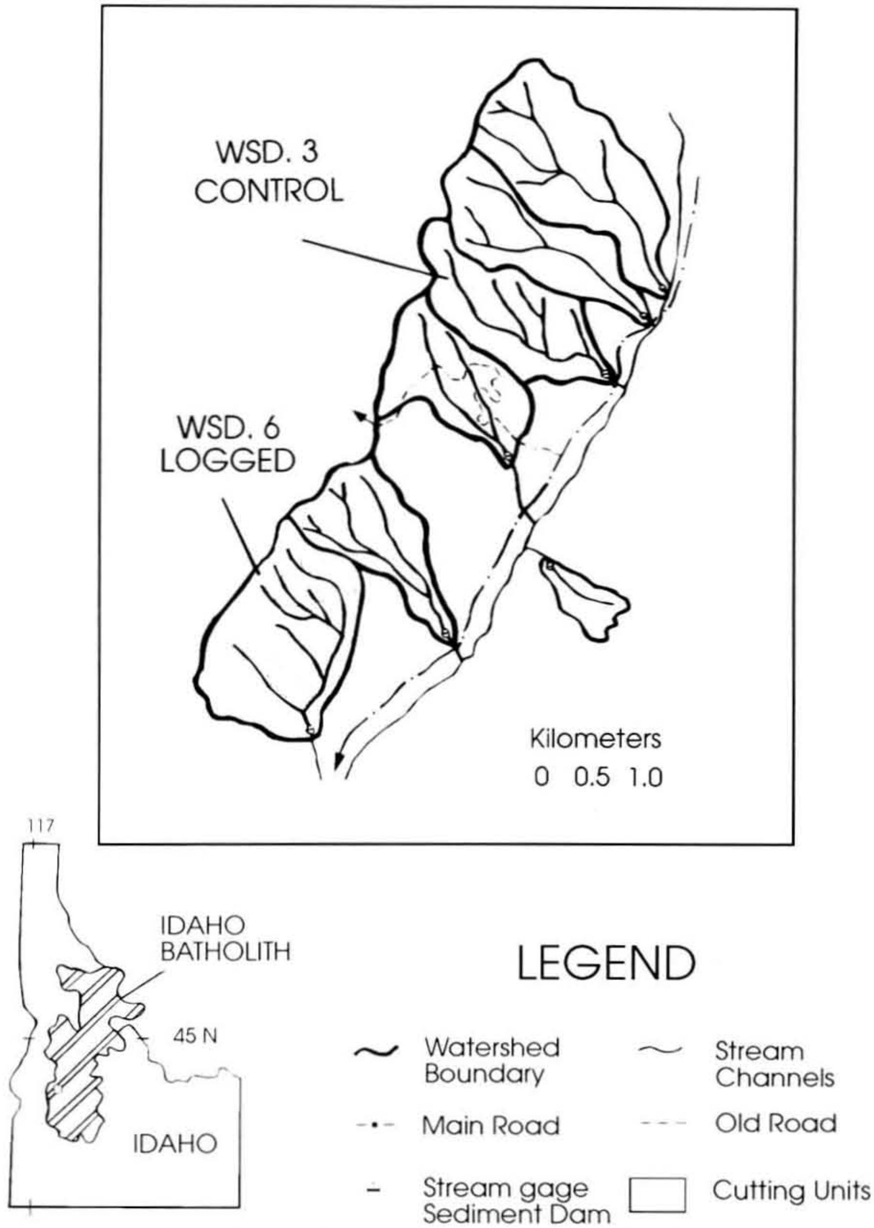

FIGURE 1. Location map and detail of the study watersheds.

developed, with A horizons ranging from 5 to 25 cm thick overlying moderately weathered granitic parent material. Shallow soils less than 20 cm deep often occur on ridges and south slopes, and scattered outcrops of granitic bedrock are found in the upper elevations of the watersheds. Soil textures are loamy sands to sandy loams, and depth to bedrock is generally less than 100 cm. Soils on the treated watershed are sandy-skeletal mixed Typic Cryorthents, sandy-skeletal mixed Typic Cryoborolls, and mixed Alfic Cryopsamments (Clayton and Kennedy 1985).

Two vegetation habitat types (h.t.) (Steele et al. 1981) predominate on the

TABLE 1.

Physiographic characteristics of study watersheds.

Characteristic	Watershed	
	WSD3 (control)	WSD6 (logged)
Area (km^2)	1.29	1.62
Elevation maximum (m)	2000	1780
Elevation minimum (m)	1450	1420
Mean slope gradient (%)	43	47
Mean hillslope azimuth (°)	127	142
Mean stream gradient (%)[a]	9.3	8.3
Stream order[b]	3	3
Drainage density (km^{-1})[b]	4.5	4.2
Mean bankfull width (m)[a]	1.0	1.4

[a] Average from data collected at 11 cross section sample sites on each stream.
[b] Taken from a 1:31680 planimetric map.

watersheds: Douglas-fir/white spirea h.t., ponderosa pine phase (*Pseudotsuga menziesii/Spirea betulifolia* h.t., *Pinus ponderosa* phase) and Douglas-fir/ninebark h.t., ponderosa pine phase (*Pseudotsuga menziesii/Physocarpus malvaceus* h.t., *Pinus ponderosa* phase). Forest stands prior to harvest had approximately equal volumes of mature or old growth ponderosa pine and Douglas-fir (Geier-Hayes 1989).

Twenty-three percent of a 162 ha watershed (WSD6) was logged, on three cutting units totaling 38 ha (Figure 1), between September and November of 1976. Helicopters were used to remove logs to loading areas outside the study area; no roads were constructed within the study watersheds. Hillslope gradients on the cutting units ranged from 24% to 97% and averaged 47%. The average slope aspect of the units was southerly (167°), with a range from 90 to 240° azimuth.

The logging prescription called for removal of all trees greater than 25 cm in diameter. This resulted in a near-clearcut condition because the stands were composed primarily of mature and old growth ponderosa pine and Douglas-fir. Stand basal area on the cutting units was 26.2 m^2/ha prior to cutting; residual stand basal area following harvest was 3.3 m^2/ha. The volume of timber removed was 263 m^3/ha, which corresponds to a merchantable volume of 23.4 M bd ft/ac (Clayton and Kennedy 1985).

Buffer strips between the cutting units and perennial streams averaged 15 m in width. The buffer strips were left undisturbed except for removal of trees that were expected to die before the next scheduled timber harvest and those that interfered with the helicopter approach to the log landing area. Logging slash that fell in the stream was removed by hand.

Slash remaining on the cutting units was lopped and scattered, then broadcast burned in November 1976 and January 1977. The fire was spotty throughout the cutting units because of the presence of scattered snow on the ground. As a result, only about 50% of the area of each cutting unit was burned. Geier-Hayes (1989) reported a fire severity rating of 2-M on two of the cutting units, and 3-M on the third, using the Ryan-Noste fire severity rating procedure (Ryan and Noste 1983).

METHODS

Streamflow and sediment responses to logging and prescribed burning were evaluated on the two study watersheds using a prelogging/postlogging, treated/control study design. Such a design makes it possible to minimize the effects of climatic differences between years. Statistical comparison of pre- and postlogging regressions between the treated and control watershed sediment and streamflow variables were made using a dummy variable model technique to test if the two regressions were parallel and coincident (Kleinbaum and Kupper 1978). In this method, pretreatment and posttreatment linear regressions of the treated vs. the control watershed can be tested for statistically significant differences. The 0.05 level of significance was used for all statistical tests.

Streamflow and sediment data were analyzed on a water year (WY = October 1 to September 30) basis. Data collected in WY 1966 through WY 1976 (the period during which both watersheds were in an undisturbed state) were used for calibration purposes.

WSD6 was logged in the fall of WY 1977, and the slash was burned in the winter of WY 1977. WSD3 was maintained as an undisturbed control throughout the duration of the study. Posttreatment sediment and streamflow responses were evaluated through WY 1986. (For the remainder of the paper, the "WY" designation will be omitted.)

Streamflow was measured at the mouth of each study watershed using standard Parshall flumes equipped with water level recorders. Periodic measurements of flow with a current meter were used to adjust stage-discharge relationships as necessary. Flow data were summarized to evaluate possible changes in total annual water yields, monthly water yields, and several snowmelt runoff parameters.

The duration of the snowmelt period usually ranges from 6 to 10 wk, so mean daily flows were judged to provide a suitable time interval for the snowmelt runoff analyses (with the exception of the instantaneous peak analyses). To eliminate baseflow effects from the snowmelt hydrographs, a separation technique similar to that described by Hewlett and Hibbert (1967) was used to discriminate between rapid and delayed snowmelt runoff. The slope of the separation line was determined by inspection of snowmelt hydrographs for all years of record for the two study watersheds.

The following information was derived from the rapid snowmelt data:

1. flow and date at the start of snowmelt;
2. number of days in period of rise, period of recession, and total snowmelt period;
3. hydrograph volume for period of rise, period of recession, and total snowmelt period;
4. peak snowmelt outflow rates averaged over periods of 1, 3, 5, 7, 10, and 15 consecutive days;
5. number of days required to accumulate deciles of the total flow volume;
6. instantaneous peak flow and the date of occurrence.

Sediment yield was measured in sediment basins behind dams located about 50 m above the stream gauge in each watershed (Figure 1). Basins were flushed in the spring after snowmelt as needed to maintain reservoir storage capacity. Detailed cross-section surveys in the spring (before and after flushing) and in the fall were used to determine the volume of sediment deposited in the basins. Cross sections were established parallel to the dam face, at 1.2 m intervals along the length of the sediment basin. Core samples of the accumulated sediments were periodically collected to establish volume-weight relationships. Sediment basin data were not available for 1983 on WSD6.

Not all of the sediment transported to the watershed mouths is deposited in the sediment basins. Some sediment, primarily in suspension, is transported through the basins and over the dams. For 7 yr during the posttreatment period, depth-integrated suspended sediment samples were collected at the sediment basin outlet with a standard DH48 sampler during the snowmelt period. Because sediment fluxes through the basins were only measured for 7 of the 21 yr, statistical comparisons of pre- and posttreatment periods were made using only the volume of sediment deposited in the basins. However, total sediment loads (basin catches plus sediment passing through the basins) expressed on a mass basis are used for estimation of onsite erosion in the discussion section. Relationships between stream discharge and suspended sediment concentrations were used with mean daily discharges to estimate annual suspended sediment production. There was a significant relationship between the estimated annual suspended sediment flux at the sediment basin overflow and the annual sediment yield measured in the sediment basins for the 7 yr during which suspended sediment was measured. This relationship was used to estimate annual suspended sediment yields for the other years. Total annual sediment yields are the sum of the annual suspended yield and the annual basin yield.

Additional studies were conducted to evaluate channel sediment storage and channel conditions. Details of the sampling design and measurement techniques are presented in Megahan (1982). The measurements include surveys of sediment volumes stored behind natural channel obstructions, and surveys of permanent cross sections to evaluate changes in streambed elevations and channel widths. Data were collected in the pretreatment years of 1975 and 1976, and the posttreatment years of 1977 through 1981. One-way analysis of variance was used to test for statistically significant differences between the logged watershed and the control watershed before and after logging.

Various methods were used to evaluate onsite erosion. Clayton (1981) conducted soil disturbance research on WSD6 just prior to logging and for 2 yr after logging; refer to the published report for a description of the methodology used. We conducted another postdisturbance erosion survey of the cutting units in 1984 and 1985 utilizing pedestaled plants, rilling, and downslope accumulations of sediment as indices of erosion. Precise quantification of total onsite erosion was not possible during this survey because data on predisturbance soil levels had not been collected. However, an inventory was made of sediment volumes accumulated in the bottoms of zero-order basins at the very head of the drainage using techniques similar to those of Tsukamoto et al. (1982). Volume of sediment deposition was estimated from 95 excavated cross sections spaced at 30 m intervals along the length of the longitudinal axes of the basin bottoms. The depth of surface accumulation of sediment deposits was determined on the basis of the difference in color between the lighter granitic sediments and the darker ash layer and underlying A horizon of the residual soil.

During the 1984 erosion survey, small-scale mass erosion was noted in one of the cutting units. This involved a single failure that propagated upslope by subsurface piping, apparently in response to progressive, small-scale liquefaction along the bottom of a 3.6 ha micro-watershed. The volume of erosion was monitored using a cross-sectioning technique described by Megahan and Bohn (1989). Reconnaissance of the untreated watershed revealed no mass erosion sites.

A detailed vegetation survey was conducted on the cutting units the summer prior to logging, and periodically up to 10 yr after logging (Geier-Hayes 1989). Data collected included plant species, plant numbers, a tally of whether or not each plot had been burned, and an ocular classification of the percentage of bare soil. Geier-Hayes' data were used in our analyses to estimate the total amount of bare soil and the continuity of bare soil openings for both burned and unburned areas.

RESULTS

STREAMFLOW

Regressions of annual water yields for WSD6 against those for WSD3 for the pretreatment and posttreatment periods produced r^2 values of 0.94 and 0.95, respectively (Figure 2). The proximity of the two regression lines and the distribution of the data points suggest that there was no detectable increase in annual water yield following logging and burning. Statistical analyses confirmed that there were no significant differences between the pretreatment and posttreatment regressions.

Monthly flow data were also analyzed with regression techniques (Figure 3). Statistical analysis showed no significant differences in monthly flows for any

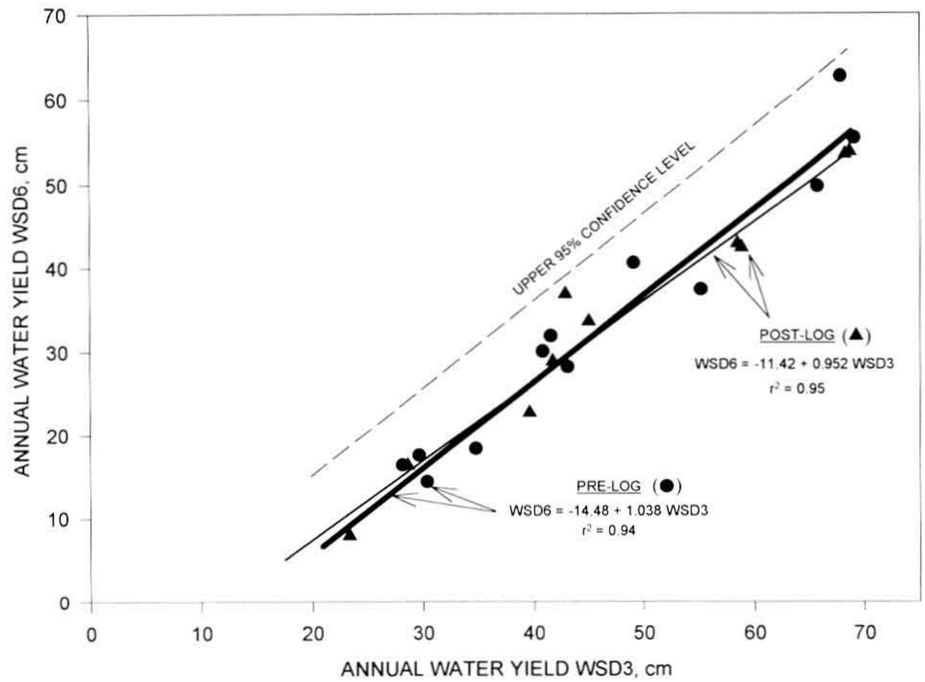

FIGURE 2. Pre- and postdisturbance regression analyses of annual water yields on WSD6 (logged and burned) vs. WSD3 (control).

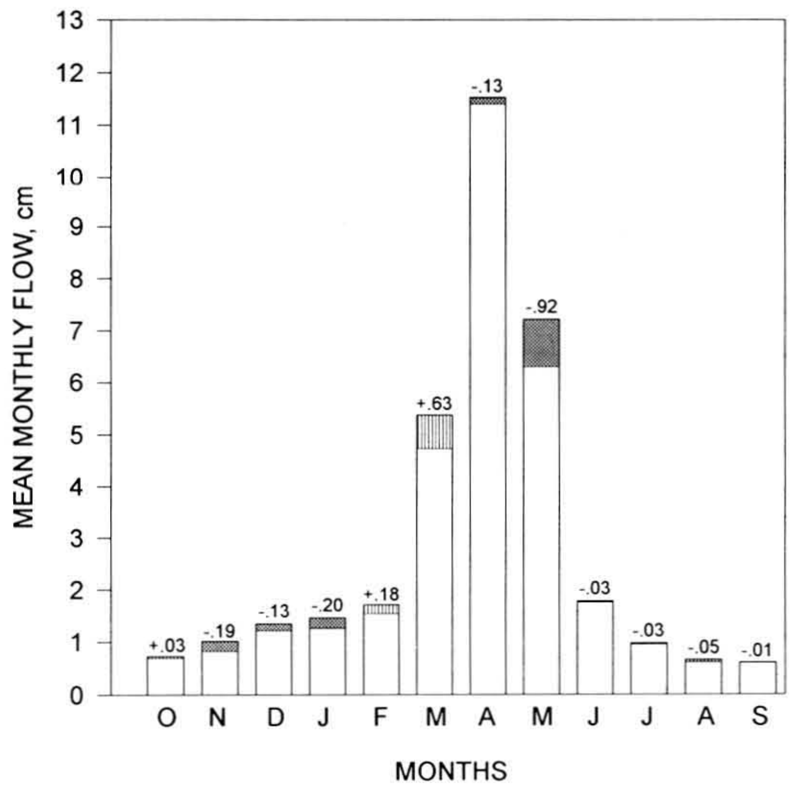

FIGURE 3. Summary of regression analyses of monthly flows before and after disturbance. Shaded areas at the top of each bar represent the difference between the measured and the predicted monthly water yield on WSD6 (logged and burned). Type of shading and numbers indicate the direction and magnitude (cm) of change.

month of the year. Changes in average monthly flows during the low-flow portions of the year were small and inconsistent. However, there is a suggestion of accelerated snowmelt runoff early in the snowmelt season, based on increased average flow rates in March and decreased flow rates in May.

Several snowmelt variables were tested for changes in regression relationships following logging and burning. Changes in peak flows are considered of particular importance because of potential impacts on channel conditions (Megahan 1979). Analyses indicated no statistically significant changes in instantaneous peak flow rates or in peak average daily snowmelt outflow rates for any of the periods evaluated (1, 3, 5, 7, 10, and 15 consecutive days). There were also no significant changes in volumes of snowmelt runoff (either in total or during the rising and falling periods), or in the flow rate at the start of snowmelt.

Snowmelt timing variables also showed little change following treatment. As discussed above, the analysis of monthly flows suggested that early season snowmelt outflows might have been accelerated following treatment. However, there were few significant changes in the time required to accumulate individual deciles of snowmelt flow. The third decile intercept and sixth decile slope tested as significantly changed; however, inspection of the data indicates no physical significance, and a Type I error is suspected. There was no significant change in the total time required to accumulate the first 50% of snowmelt runoff.

Analyses of other variables testing the duration of melt, such as the number of days in the period of rise, period of recession, and total snowmelt period, showed no statistically significant changes. The dates of start of melt and instantaneous peak occurrence also showed no significant change.

SEDIMENT YIELDS

Pre- and posttreatment annual sediment volumes measured in the sediment basins are plotted in Figure 4. The data were nonlinear and exhibited nonuniform variance; therefore, a logarithmic transformation of the data was used to successfully linearize the relationship and homogenize the variance. There was a statistically significant posttreatment increase in annual sediment volumes, with the largest increases occurring during the years with highest sediment volumes.

The increases in annual sediment volume appear to continue 10 yr after disturbance. The pretreatment regression between WSD3 and WSD6 was used to calculate the annual sediment basin volumes that would have been expected on WSD6 during the posttreatment years, assuming no disturbance had occurred. The expected and the measured annual sediment basin volumes were then converted to a mass basis using the bulk density data and adjusted to include the suspended sediment portion of the total sediment load. The expected and measured total sediment production were then compared for these posttreatment years to determine the effects of logging and burning (Table 2). Annual sediment

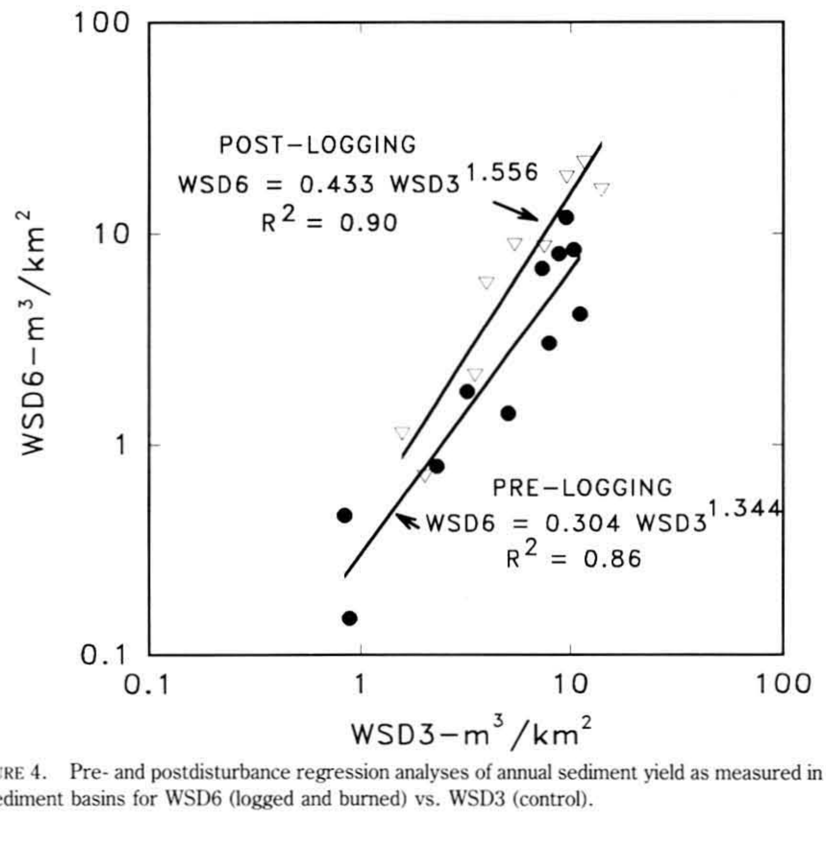

FIGURE 4. Pre- and postdisturbance regression analyses of annual sediment yield as measured in the sediment basins for WSD6 (logged and burned) vs. WSD3 (control).

TABLE 2.

Effects of disturbance on annual sediment yields.

Year	Sediment yield (t/km²/yr) WSD3 (control) measured	WSD6 (logged) measured	WSD6 (logged) predicted[1]	Increase from disturbance
1977	3.37	2.55	2.19	0.37
1978	6.91	10.02	3.91	6.11
1979	2.83	1.81	2.08	−0.27
1980	10.79	12.70	7.42	5.28
1981	6.05	4.16	3.21	0.97
1982	22.39	22.11	16.48	5.63
1983	19.53	—	—	—
1984	14.82	26.46	10.72	15.74
1985	9.09	12.29	5.36	6.92
1986	19.22	36.03	13.64	22.40
Mean	11.50	14.24	7.22	7.01

[1] Sediment yield predicted using prelogging regression of WSD6 against WSD3 and adjusted for bulk density of the sediment and the trap efficiency of the sediment basins.

basin yields on WSD6 in the undisturbed state would expected to average 7.2 t/km^2/yr during the posttreatment years ("t" denotes metric tons). However, measured sediment yields for the period averaged 14.2 t/km^2/yr, an increase of 7.0 t/km^2/yr (or 97%), following logging and broadcast burning. Adjusted to the 1.62 km^2 watershed area, this represents a total increase of about 114 t of sediment in the 10 yr since disturbance.

Channel Studies

Analysis of variance showed no statistical differences between the average volume of sediment stored behind natural obstructions in the two study channels in any individual pretreatment or posttreatment year (Figure 5). The average storage was consistently less on the unlogged watershed for all years except 1977, the first posttreatment year. This reversal in pattern suggests the possibility that removal of logging slash from the channel may have disturbed some natural channel obstructions, thereby reducing total sediment storage behind obstructions during the first year after disturbance.

Changes in volume of sediment storage on the channel bottom were evaluated by comparing the net change in the cross-section area of lithic sediments on plotted cross sections (Figure 6). Channel bed elevations in the sample streams are erratic in response to shifting bedforms. Such variation is greatly magnified in these small streams because even small natural channel obstructions aggravate lateral shifting of the bed and cause temporary storage and release of sediments. In addition, many obstructions, especially of the debris type, are unstable and tend to shift location with changes in flow and the supply of organic matter (Megahan 1982). The wide confidence bands for the data reflect this large variation.

A series of statistical tests was used to evaluate whether part of the variance could be explained by site or flow factors. Multiple regression analysis was used

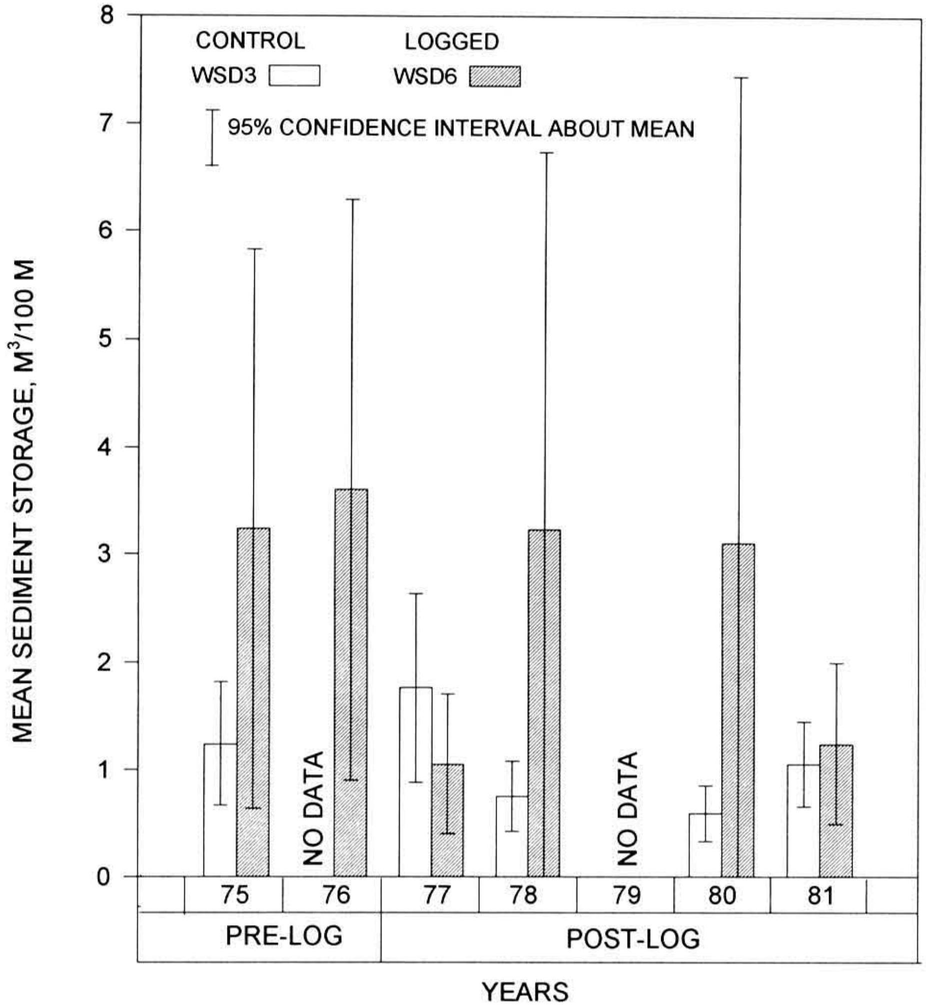

FIGURE 5. Pre- and postdisturbance average channel sediment storage behind obstructions on WSD3 (control) and WSD6 (logged and burned).

to test the effects of channel gradient, annual water yield, and the annual peak mean daily flow. None of the variables tested were statistically significant. The lack of significance of either site or flow factors precluded the use of covariance to test for the effects of logging and burning. Instead, paired t-tests were used to evaluate changes in average cross-section area of lithic sediments by comparing differences at individual cross sections for each time increment. No statistical differences were detected from one year to the next on either of the streams. Finally, a one-way analysis of variance showed no statistical differences in mean cross-section area of lithic sediments between streams.

Channel bottom width measurements derived from the cross-section survey data were used to evaluate possible changes in sediment storage caused by erosion or deposition along the stream banks. Average bottom widths by stream and year are shown in Figure 7. The width of the channel bottom in WSD6 was consistently greater than that of WSD3, reflecting the higher peak flows on

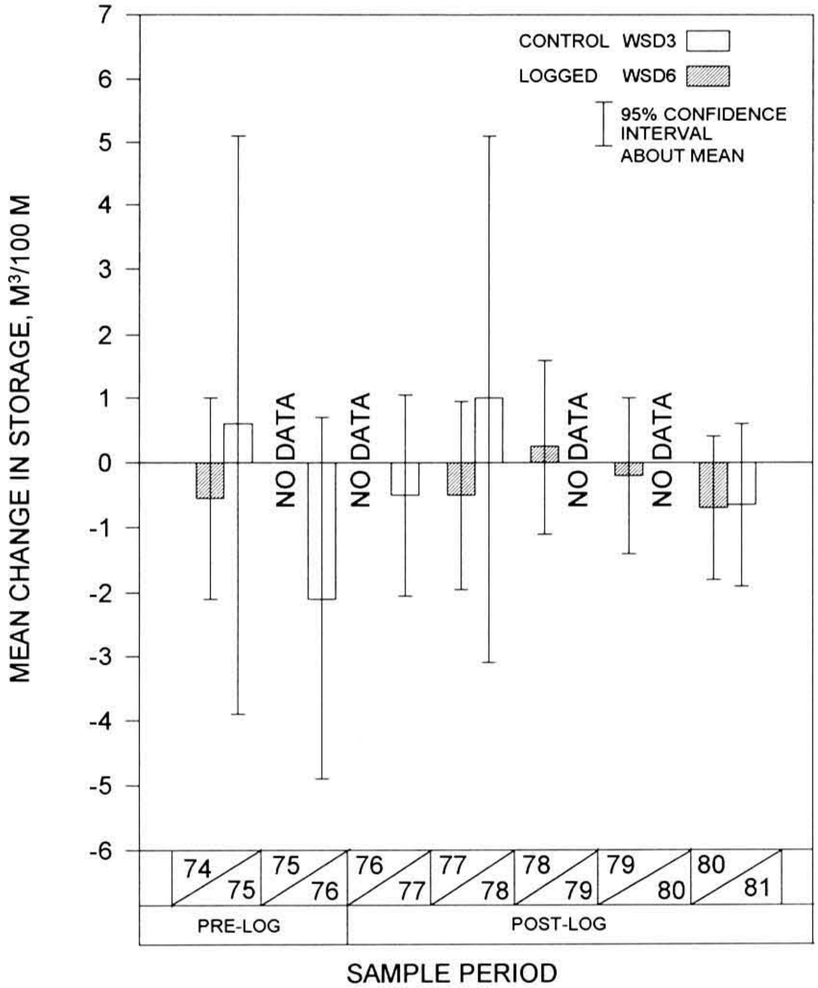

FIGURE 6. Pre- and postdisturbance net changes between years in channel bottom lithic sediment volumes on WSD3 (control) and WSD6 (logged and burned).

WSD6. Average bottom widths appear to increase somewhat on WSD6 in the posttreatment years of 1977 and 1978. Paired t-tests were used to test for changes in bottom widths by comparing successive measurements of individual cross sections on each of the study streams. There were no significant differences for any years on either watershed, except between 1979 and 1980 on the unlogged watershed.

Overall, measured increases and decreases in channel sediment storage compensated for each other, and no trends were detected. There are two plausible explanations for a lack of response in sediment storage. The sediment supplied to these steep channels may have been diffuse over time and space to the point that changes in channel sediment storage could not be detected with the sampling techniques used. Another explanation is that most of the sediment supplied to these channels was transported to the watershed mouth.

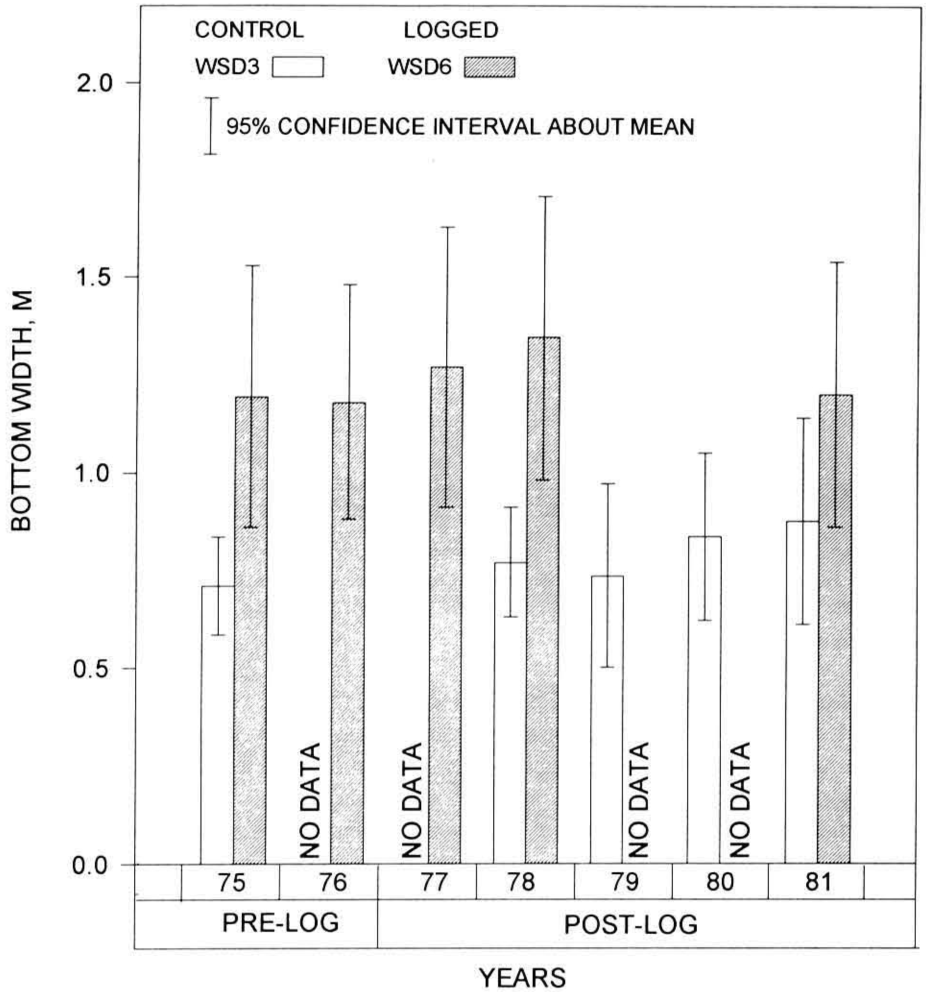

FIGURE 7. Pre- and postdisturbance average channel bottom widths for WSD3 (control) and WSD6 (logged and burned).

EROSION IN THE CUTTING UNITS

The percent bare soil and bare soil opening lengths over time for burned and unburned portions of the cutting units, as calculated from Geier-Hayes' (1989) data, are presented in Figure 8. Burned and unburned areas each constituted about half of the total area of the cutting units. The first year after disturbance (1977), bare soil averaged about 50% on the burned areas, and decreased to 35 and 30% in 1978 and 1986, respectively. Geier-Hayes (pers. comm.) attributes the decrease in bare soil on the burned areas primarily to the growth of snowbrush ceanothus (*Ceanothus velutinus* Dougl.), which, following fire, resprouts from existing plant remnants (roots and root crowns) and germinates from seed buried in the soil.

The percentage of bare soil was consistently lower on the unburned areas, with respective averages of 3, 4, and 19% in 1977, 1978, and 1986. The 19% figure is

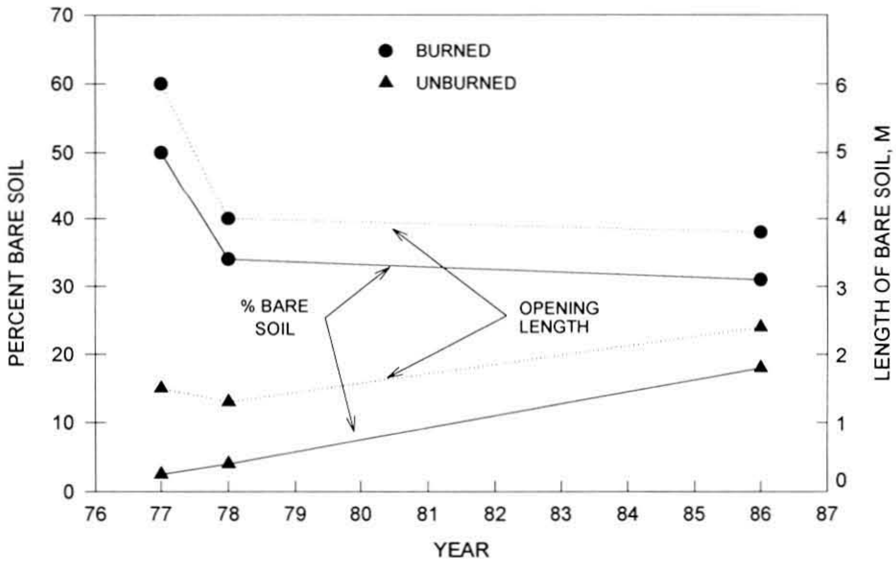

FIGURE 8. Postdisturbance percentage of bare soil and lengths of bare soil openings on burned and unburned areas within the cutting units on WSD6.

comparable to the 15% reported by Clayton (1981) for undisturbed slopes in the area. Unlike the burned areas, percentage of bare soil on the unburned areas tended to increase over time, probably in response to the progressive decay of logging slash.

Trends in length of continuous bare soil openings were similar to those for percent bare soil. Lengths were greatest on the burned plots, with averages decreasing from 6.0 to 4.0 to 3.8 m for the three measurement dates, compared with values of 1.6, 1.3, and 2.3 m on the unburned areas for the same dates.

Considering the inherent high erodibility of these soils, and the slow recovery of vegetation on burned areas, it is not surprising that surface erosion continued in the burned areas throughout the life of the study. About 60 m^3 of soil were stored in the bottom of zero-order basins as a result of upslope surface erosion. Field crews estimated that as much, or more, sediment was deposited in other locations.

Analysis of the cross-section data from the landslide site showed that 6.1 t of soil eroded from the failure and was delivered directly to the stream between 1977 and 1984. By 1986 this total had increased to 7.0 t of sediment. If all of this material reached the mouth of the watershed, it would constitute about 6% of the total accelerated posttreatment sediment yield.

DISCUSSION

Average annual sediment yields showed a statistically significant increase following logging and burning of 7.0 t/km^2/yr or 97%. Greatest effects occurred during years with highest sediment yields. Accelerated sedimentation showed no signs of abating 10 yr after disturbance. These increases in annual sediment yields are representative of what might be expected in the southern Idaho Batholith based on annual sediment yield data from six other study watersheds in the vicinity. Four of the watersheds are located nearby in the Silver Creek Study Area; the other two are located 75 km to the north in the South Fork of the Salmon River drainage. Data are available for all six watersheds for the calibration period of the present study and represent undisturbed forest conditions in all cases (unpublished data, Intermountain Research Station). The average annual sediment yield for the six study watersheds ranged from 4.2 to 14.6 t/km^2/yr, bracketing the average of 5.2 t/km^2/yr for the present study watershed for the same time period.

The question arises as to what caused the long-term accelerated sediment yield. Analyses of streamflow data indicate that the increased sediment yields were not the result of channel erosion caused by increased streamflow rates. This is supported by the channel study data, which found no significant changes in variables indicative of channel scour.

Examination of watershed slopes suggested that the accelerated sedimentation was caused by active mass and surface erosion within the cutting units. The mass erosion consisted of a single progressive failure that accounted for a maximum of 6% of the total accelerated sediment yield. Megahan and Bohn (1989) attributed the failure primarily to localized changes in groundwater regimes following logging, with reduced root strength a secondary factor.

The remainder of the increased sediment yield was apparently caused by accelerated surface erosion that continued on the cutting units 10 yr after treatment as a result of long-term exposure of bare soil. The detailed plant surveys showed that percent bare soil and length of bare soil openings were considerably greater on burned areas of the cutting units. Geier-Hayes (1989) reported that cover of shrubs and herbs was below predisturbance levels on both forest habitat types 10 yr after disturbance; she attributed the slow recovery to the prescribed burning.

Such a slow recovery of vegetation reflects the extremely harsh site conditions within the south-facing cutting units. Soils are shallower than on other aspects, with A horizons averaging 15 cm overlying C horizons that extend to bedrock at an average depth of 60 cm (J.L. Clayton, pers. comm.). Texture of both horizons is commonly gravelly, loamy, coarse sand or gravelly, coarse, sandy loam. Water available to plants under these conditions is less than 10% by volume (Clayton and Jensen 1973), or less than 6 cm on average. Based on the average slope gradient and aspect of the cutting units, the potential incident solar radiation load on the units is about 99% of the maximum possible at that latitude (Buffo et al. 1972).

The combination of low soil moisture holding capacity, high incident solar radiation, and hot, dry summers contribute to extreme soil moisture stresses and slow revegetation. In addition, the prescribed burning consumed much of the litter and killed most of the residual understory vegetation. Thus there was no long-term source of litter to protect the soil surface. The resulting harsh site conditions restricted vegetation regrowth (except for snowbrush ceanothus, which is stimulated by fire) and led to long-term accelerated surface erosion and sediment yields.

Similar conditions do not occur on north aspect slopes in the area. Megahan and Molitor (1975) reported on the erosional effects of a clearcut and subsequent wildfire on a small, north-facing watershed about 2 km from the site of the present study, and in the same elevation range. The wildfire was extremely hot, consuming all duff and litter and all logging debris less than 20 cm in diameter, as well as

95% of all shrub stems. Vegetation recovery was rapid, with cover densities of 3, 16, 60, and 100%, respectively, for 0, 1, 2, and 3 yr after burning. This was reflected in a decrease in sediment yields, from 140 t/km^2/yr the first year following the fire to no detectable erosion or sedimentation in the third year. (Second and third year cover and erosion data are unpublished data on file at USDA Forest Service, Forestry Sciences Laboratory, Boise, ID.)

Accelerated sediment yields averaging 97% that persist for 10 yr are of great concern in the Idaho Batholith. Much of the sediment is coarse-grained material that moves as bedload and can have serious consequences for fish populations (Seyedbagheri et al. 1987). In addition to the potential for downstream damages, increased sediment yields have implications for site productivity impacts due to onsite erosion.

The total increase in sediment yield over the 10 yr posttreatment period was 114 t of which 7 t was attributed to a mass failure site. Assuming the remaining 107 t was caused by accelerated surface erosion on the logged area, the average annual accelerated erosion was 10.7 t/yr from a logged area of 38 ha. However, only 50% of the logged area was burned; the remainder had less bare soil than surrounding unlogged areas because of accumulations of logging slash. Thus, it is reasonable to assume that the accelerated surface erosion occurred on the burned portions of the area logged, an area of 19 ha. On this basis, the unit area erosion rate was 0.56 t/ha/yr.

This erosion rate requires adjustment for sediment delivery from the burned areas of the cutting units to the sediment basin at the watershed mouth. Megahan et al. (1986) developed sediment budgets for three other watersheds in the Silver Creek Study Area, which were similar in size and other characteristics to the logged watershed. Sediment delivery ratios the first year following road construction ranged from 2 to 15% and averaged 7%. If we assume that the average delivery ratio applies to the logged watershed in the present study, the average annual erosion rate on the burned areas would be about 8.0 t/ha/yr.

Clayton and Megahan (1986) developed estimates of long-term erosional denudation rates for WSD6 in the undisturbed state using a Monte Carlo simulation technique. They reported a rate of 0.122 t/ha/yr. Thus, the 10 yr average posttreatment erosion rate represents an accelerated erosion rate of about 66 times greater than the undisturbed rate.

Accelerated soil loss can be considered in relation to the total nutrient pool of a site. Nitrogen is often the growth-limiting nutrient on forest lands in the northwestern United States (Gessel 1968) and is likely to be in short supply on the shallow, granitic soils of the study area. The accelerated soil loss on the burned area averages about 0.7 mm depth per year. Assuming this loss is from the A horizon of the common soil on the logging units, this amounts to an average annual nitrogen loss of 5.6 kg/ha/yr (J.L. Clayton, pers. comm.). Although snowbrush ceanothus supports nitrogen-fixing organisms, coverage of this species was still limited after 10 yr, leaving precipitation as the primary source of nitrogen. Clayton and Kennedy (1985) report an average annual nitrogen input from precipitation of 1.5 kg/ha/yr in the study area. However, it is likely that most of this is leached from the site because of the lack of vegetative cover and litter. Because of the limited ability of the site to retain nitrogen coming from any source, the accelerated losses from erosion must be viewed as detrimental to productivity until vegetation and soil organic matter levels are restored.

This exercise to extrapolate increases in sediment yields measured at the mouth of this small watershed to increases in on-site surface erosion is based on many assumptions about sediment delivery and where on-site erosion occurred. However, it is useful in demonstrating that impaired site productivity may be an important concern following helicopter logging and broadcast burning of slash on similar harsh sites.

CONCLUSIONS AND RECOMMENDATIONS

Helicopter logging and subsequent broadcast burning of slash disturbed 23% of a 162 ha study watershed. The logging approximated a clearcut and was confined to south aspects. Statistically significant increases in annual sediment yields averaged 97% in the 10 yr following disturbance, with the largest increases occurring in the years of highest yields. The increases in sediment yields did not appear to be caused by changes in streamflow regimes or associated channel erosion. Rather, long-term accelerated surface and mass erosion on the watershed slopes was judged to be the primary cause. A maximum of 6% of the increase in sediment yield was associated with a localized, progressive mass failure; the remainder was due to surface erosion.

Most of the accelerated surface erosion was attributed to the broadcast burning rather than the helicopter logging, because the burning caused the majority of the exposure of bare soil. Shallow, coarse-textured soils coupled with high radiation loads on south slopes of the Idaho Batholith cause extremely high soil moisture stresses during the growing season and lead to slow vegetation regrowth following burning. The continued exposure of highly erodible granitic soils was the primary cause of the long-term accelerated surface erosion and sediment yields. Such responses are limited to south aspects in this area.

The magnitude and duration of accelerated sedimentation raises concern for both downstream fish populations and onsite productivity. The estimated erosion rate on the burned areas was 8 t/ha/yr, 66 times the long-term average rate for undisturbed slopes in the study area.

In terms of erosion and sedimentation, the magnitude of the effects of broadcast burning used in this study appears to far outweigh the minimal effects of helicopter logging when applied on Idaho Batholith south slopes similar to those in the study. In such situations, piling and burning, or better yet, no burning, is advisable to reduce sedimentation. Lopping and scattering of logging slash provides an option to prescribed burning. Although this practice is not as effective in reducing fire hazards as prescribed burning, it does speed the breakdown of fine fuels and helps avoid concentration of fuels and reduce burn intensity. Reduced burn intensity on coarse textured, granitic soils reduces the occurrence of fire-induced soil water repellancy (DeByle 1973) and increases the survival of any residual tree cover, thus minimizing surface erosion (Connaughton 1935). In addition, lopping and scattering maximizes site protection from erosion and assures maintenance of the soil nutrient capital in the absence of wildfire (Graham et al. 1994). If broadcast burning is a necessity, burning should be done when duff moisture and soil moisture levels are high, to minimize fire severity (Frandsen and Ryan 1986). Otherwise, some type of silvicultural practice that leaves more of the residual tree stand (such as a light shelterwood or seed tree cutting), rather than the near-clearcut that was used on the study area, should be considered. With these alternatives, slash loadings and fire severity would be reduced, and the residual stand would reduce incident radiation and provide a source of litter to protect the soil surface.

LITERATURE CITED

BETHLAHMY, N. 1967. Effect of exposure and logging on runoff and erosion. USDA For. Serv. Res. Note INT-61. 7 p.

BUFFO, J., L.J. FRITSCHEN, and J.L. MURPHY. 1972. Direct solar radiation on various slopes from 0 to 50 degrees north latitude. USDA For. Serv. Res. Pap. PNW-142. 74 p.

CLAYTON, J.L. 1981. Soil disturbance caused by clearcutting and helicopter yarding in the Idaho Batholith. USDA For. Serv. Res. Note INT-305. 7 p.

CLAYTON, J.L., and C.E. JENSEN. 1973. Water retention of granitic soils in the Idaho Batholith. USDA For. Serv. Res. Pap. INT-143. 20 p.

CLAYTON, J.L., and D.A. KENNEDY. 1985. Nutrient losses from timber harvest in the Idaho Batholith. Soil Sci. Soc. Am. J. 49:1041–1049.

CLAYTON, J.L., and W.F. MEGAHAN. 1986. Erosional and chemical denudation rates in the southwestern Idaho Batholith. Earth Surf. Proc. Landforms 11:389–400.

CONNAUGHTON, C.A. 1935. Forest fires and accelerated erosion. J. For. 33:751–752.

DEBYLE, N.V. 1973. Broadcast burning of logging residues and the water repellancy of soils. Northwest Sci. 47:77–87.

FRANDSEN, W.H., and K.C. RYAN. 1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. Can. J. For. Res. 16:244–248.

GEIER-HAYES, K. 1989. Vegetation response to helicopter logging and broadcast burning in Douglas-fir habitat types at Silver Creek, central Idaho. USDA For. Serv. Res. Pap. INT-405. 24 p.

GESSEL, S.P. 1968. Progress and needs in tree nutrition research in the northwest. Forest fertilization: Theory and practice. Tennessee Valley Authority, National Fertilizer Development Center Muscle Shoals, AL. p. 216–225.

GRAHAM, R.T., et al. 1994. Managing coarse woody debris in forests of the Rocky Mountains. USDA For. Serv. Res. Pap. INT-477. 12 p.

HEWLETT, J.D., and A.R. HIBBERT. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. Proc. Forest Hydrology, National Science Foundation Advanced Science Seminar. Pergamon Press, London. p. 275–290.

KLEINBAUM, D.G., and L.L. KUPPER. Applied regression analysis and other multivariate methods. Duxbury Press, North Scituate, MA.

MEGAHAN, W.F. 1975. Sedimentation in relation to logging activities in the mountains of central Idaho. P. 74–82 *in* Proc. Present and prospective technology for predicting sediment yields and sources: Sediment-yield workshop. USDA Agric. Res. Serv. Publ. ARS-S-40.

MEGAHAN, W.F. 1979. Channel stability and channel erosion processes. Proc. Workshop on Scheduling timber harvest for hydrologic concerns. USDA For. Serv., Pacific Northwest Reg. and Pacific Northwest For. and Range Exp. Sta.

MEGAHAN, W.F. 1981. Nonpoint source pollution from forestry activities in the western United States: Results of recent research and research needs. P. 92-151 *in* Proc. U.S. forestry and water quality: What course in the 80's?. Water Pollution Control Federation, Washington, DC.

MEGAHAN, W.F. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith. P. 114–121 *in* Proc. Workshop on Sediment budgets and routing in forested drainage basins, Swanson, F.J., et al. (tech. eds.). USDA For. Serv. Gen. Tech. Rep. PNW-141.

MEGAHAN, W.F., and C.C. BOHN. 1989. Progressive, long-term slope failure following road construction and logging on noncohesive, granitic soils of the Idaho Batholith. P. 501–510 *in* Proc. Symp. Headwaters hydrology, WOESSNER, W.W., and D.F. POTTS (eds.). Bethesda, MD, Am. Water Res. Assoc.

MEGAHAN, W.F., and D.C. MOLITOR. 1975. Erosional effects of wildfire and logging in Idaho. P. 423–444 *in* Proc. Watershed management symp. New York, Am. Soc. Civil Engineers, Irrigation and Drainage Division.

MEGAHAN, W.F., K.A. SEYEDBAGHERI, T.L. MOSKO, and G.L. KETCHESON. 1986. Construction phase sediment budget for forest roads on granitic slopes in Idaho. P. 31–39 *in* Proc. Drainage basin sediment delivery, Hadley, R.F. (ed). IAHS Publ. No. 159. Walingford, Oxon, UK, Int. Assoc. Hydrolog. Sci.

ROSS, C.P. 1963. Modal composition of the Idaho Batholith. U.S. Geol. Surv. Prof. Pap. 475–C.

RYAN, K., and N. NOSTE. 1983. Evaluating prescribed fires. P. 230–238 *in* Proc., Symp. and Workshop on Wilderness Fire, Lotan, J.E. et al. (tech. coords.). USDA For. Serv. Gen. Tech. Rep. INT-182.

SEYEDBAGHERI, K.A., M.L. MCHENRY, and W.S. PLATTS (comps.). 1987. An annotated bibliography of the hydrology and fishery studies of the South Fork Salmon River. USDA For. Serv. Gen. Tech. Rep. INT-235. 27 p.

STEELE, R., R.D. PFISTER, R.A., RYKER, and J.A. KITTAMS. 1981. Forest habitat types of central Idaho. USDA For. Serv. Gen. Tech. Rep. INT-114. 138 p.

TSUKAMOTO, Y., T. OHTA, and H. NOGUCHI. 1982. Hydrological and geomorphological studies of debris slides on forested hillslopes in Japan. P. 89–98 *in* Proc. Recent developments in the explanation and prediction of erosion and sediment yield, Walling, D.E. (ed.). Int. Assoc. Hydrol. Sci. Publ. No. 137.

Manuscript received June 21, 1994

AUTHORS AND ACKNOWLEDGMENTS

Walter F. Megahan is Research Hydrologist, National Council of the Paper Industry for Air and Stream Improvement, 615 W Street, Port Townsend, WA 98368. He is retired from the USDA Forest Service, Intermountain Research Station, where he was employed during the conduct of this study. John G. King and Kathleen A. Seyedbagheri are Research Hydrologist and Hydrologist, respectively, USDA Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, 316 E. Myrtle St., Boise, ID 83702. The authors are grateful to the many Watershed Research Unit personnel of the Boise Forestry Sciences Lab, past and present, who participated in the collection and analysis of data for this study; to Kathleen Geier-Hayes, who shared her data on fire effects and vegetation response; to James Clayton, for assistance in interpreting the site productivity implications of the research results; and to the manuscript reviewers.