

Hydrologic Effects of Clearcutting and Wildfire on Steep Granitic Slopes in Idaho

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Many of the environmental impacts of logging and wildfire are caused by changes in the hydrologic response of slopes after disturbances. This study was conducted to evaluate changes in inflow, storage, and outflow for 3-year periods before and after clearcut logging and wildfire on two steep, granitic microwatersheds in Idaho. Clearcutting alone and clearcutting plus wildfire increased annual peak snow water equivalent and snowmelt rates an average of 41% and 30%, respectively. The greater volume and rate of snowmelt caused respective increases in the peak piezometric rise and in total piezometric storage, amounting to 47% and 27%. Accordingly, the total volume of subsurface flow intercepted by the roadcut was increased 96% and was accompanied by 27% greater peak flow rates. None of the above responses were detectable on an adjacent watershed that was burned by wildfire alone. Evapotranspiration was reduced on both watersheds after clearcutting or wildfire, as indicated by increases in the unsaturated soil water content at the end of the growing season amounting to 44 and 72%, respectively. Accelerated mass erosion on clearcut slopes, and accelerated surface and mass erosion on roads and in channels below roads, can result from such changes.

INTRODUCTION

Studies show that removal of a large portion of timber from a forested watershed increases total runoff. Causal factors include reduced interception losses, reduced transpiration, and increased snow accumulation and melt rates [Anderson *et al.*, 1976]. Except during extreme high-intensity rainstorms, overland flow is uncommon on undisturbed, forested slopes in Idaho. Even disturbance does not generate overland flow on many forested watersheds in Idaho and elsewhere. Rothacher [1965] reported that overland flow is almost unknown on clearcut areas temporarily devoid of vegetation on western Oregon watersheds. Thus it appears that such forest uses as logging are not apt to cause overland flow, except in localized situations where infiltration rates are reduced (by road construction, log skidding, slash burning, etc.). If timber harvest increases total runoff but not overland flow, as is commonly the case in Idaho, then deep groundwater flow, shallow flow in the soil zone, or both must increase.

Whipkey [1965] noted that saturated subsurface flow probably will occur when the land is sloping, surface soil is permeable, a water-impeding layer is near the surface, and large volumes of water are added to the soil. Based on these criteria, conditions are ideal for subsurface flow in the Idaho batholith. This extensive mountainous area (41,400 km²) covers a large portion of central Idaho (Figure 1). Typically, shallow, coarse-textured soils (loamy sands to sandy loams) are found on steep slopes that average 60% or more. Although the granitic bedrock exhibits various degrees of weathering and fracturing, it usually impedes the downward flow of water. Relatively deep snowpacks annually release large volumes of water to the soil within short periods; this water rapidly infiltrates and flows downward until it reaches the bedrock surface. Continued inflow of water creates a saturated layer at the bedrock surface and causes subsurface flow downslope along the bedrock surface. Infrequent, large, cyclonic storms, sometimes coupled with snowmelt, may also generate subsurface flows in this area.

The depth of the zone of soil saturation is a critical factor, regulating slope stability [Swanston, 1967; Wu, 1976; Ward, 1976]. Thus slope stability may decrease in response to increased subsurface flow after logging. Loss of root strength after logging has also been shown to contribute to increased landslide activity [Gray, 1978; Ziemer and Swanston, 1977; Ziemer, 1981]. The combination of increased depth of the saturated soil zone and reduced root strength following forest removal may well have a synergistic effect that further accelerates landslide activity after logging in mountainous areas [Gray and Megahan, 1981].

Roads can accelerate erosion on slopes in Idaho [Megahan and Kidd, 1972] partly because of overland flow caused by reduced infiltration on the components of the road prism. In addition, overland flow can be generated in mountain lands where it is necessary to cut into a slope to provide a level roadbed. When this happens, the incision into lower soil horizons or bedrock on moderate-to-steep slopes causes a large portion of the subsurface flow to be intercepted by the cut slope of the road and be transformed to surface flow. Runoff from this source leads to increased mass and surface erosion on roads during snowmelt periods and large rainstorms [Megahan, 1972].

The objective of the present study was to evaluate the effects of clearcut logging on the volume and rate of inflow, storage, and outflow of water from the study watersheds, primarily during the snowmelt period. Less than 1 year after the logging, wildfire caused the study objectives to be expanded to evaluate the effects of burning as well.

THE STUDY AREA

The two study watersheds of 0.97- and 0.32-ha size are located in the Pine Creek drainage, a tributary of the Middle Fork of the Payette River drainage in Idaho (Figure 1). These first-order watersheds average about 1530-m elevation and are representative of headwater drainages found in the midelevation, nonglaciated landscapes of the Idaho batholith. No surface flow or channel formation is evident in the drainage bottoms of these watersheds.

Prior to clearcut logging on watershed 1 in 1972, vegetation on the watersheds was undisturbed, except in the immediate vicinity of data collection sites, where some clearing of under-

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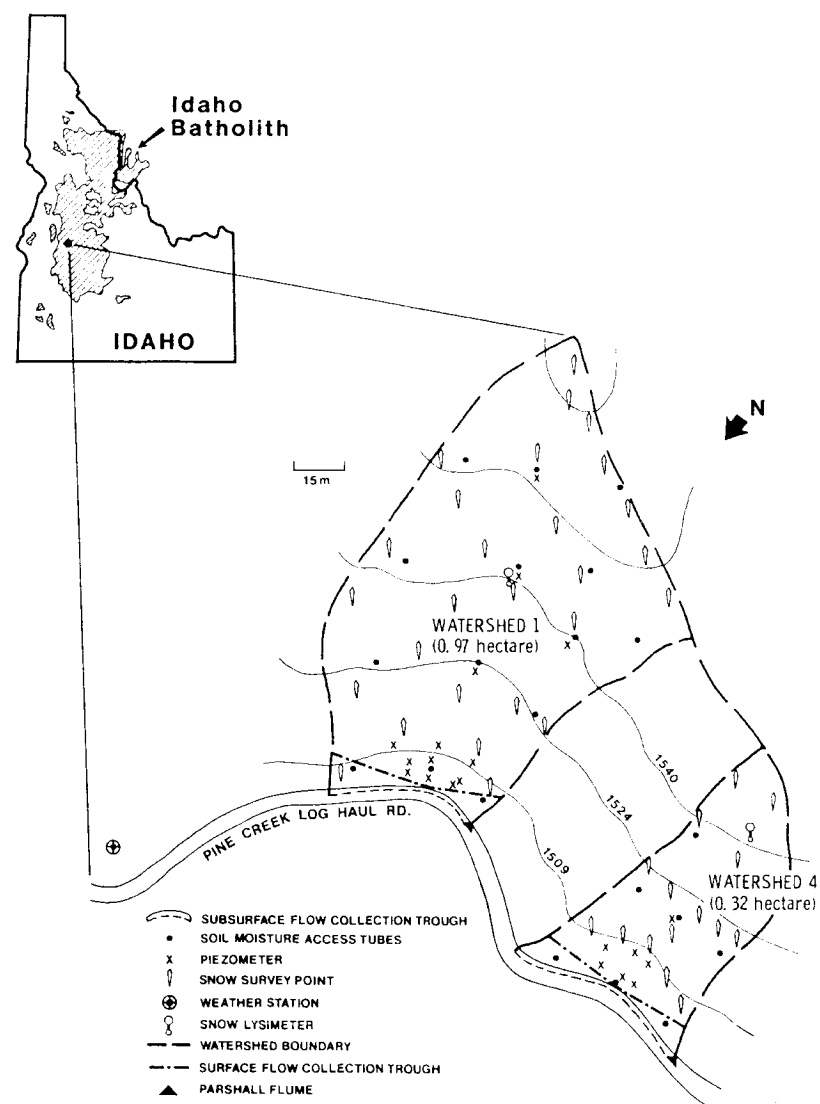


Fig. 1. Location map and detail of slope hydrology study.

story vegetation was necessary. The forest site is classified as a Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco)–Ninebark (*Physocarpus malvaceus* [Greene] Kuntze) habitat type [Steele *et al.*, 1981]. Tree cover consisted of a mature stand of ponderosa pine (*Pinus ponderosa* Laws.) averaging 65 cm in diameter (breast high) and lesser amounts of second-growth Douglas fir averaging about 35 cm in diameter. Predisturbance tree crown cover averaged 43% and 63% on the uncut and clearcut watersheds, respectively.

Slope gradients range from 35% to more than 70%, and aspects vary from northeast to northwest. The soil is classified as Koppes loamy coarse sand and is a member of the sandy-skeletal mixed family of Typic cryoborolls [Nelson, 1976]. Soil depths range from 15 cm on ridges to about 120 cm in drainage bottoms. In the undisturbed state, surface soils are almost entirely covered by litter up to 3 cm in depth. Soils are poorly developed, exhibiting only shallow A and C horizons. The transition between the C horizon and the moderately weathered and fractured, quartz monzonite bedrock is not readily apparent; detection in the field is based primarily on ease of excavation. The saturated hydraulic conductivity of the subsurface flow zone (primarily the C horizon) averages about 0.95 cm

min⁻¹ (W. F. Megahan, unpublished data, 1972), whereas the saturated hydraulic conductivity of bedrock similar to that on the study area averages only about 0.007 cm min⁻¹ [Hampton *et al.*, 1974].

Annual precipitation at the study area averages approximately 890 mm. A large proportion occurs as snowfall, resulting in an average maximum snowpack of about 1.5 m, containing 360 mm of water equivalent. The spring snowmelt period averages about 6 weeks, with maximum daily melt rates of up to 66 mm.

STUDY DESIGN AND DATA COLLECTION

Study Design

The original study design was a paired watershed approach with a calibration period from 1970 to 1972. The effects of clearcutting watershed 1 in 1972 were to be monitored from 1973 to 1975 and compared with the control watershed. Hydrologic responses to be evaluated included total snow accumulation and snow ablation rates, incoming shortwave solar radiation, piezometric rise and storage in the saturated subsurface flow zone, depth of unsaturated soil moisture in the pri-

mary transpiration zone, and volume and rate of subsurface flow intercepted by the road cut slope.

Timber harvest activities were deliberately scheduled for late fall 1972 when both watersheds had reached their annual minimum soil moisture content. Transpiration during the subsequent winter and spring was minimal in comparison with the late spring to early fall growing period. Therefore, differences in hydrologic responses in spring 1973 were largely due to the effects of logging on snow accumulation and melt rates alone. Under the original study design, the 1974 and 1975 spring snowmelt responses would have included the effects of changes in snow accumulation and melt plus changes in evapotranspiration.

In November 1972, all timber (about $200 \text{ m}^3 \text{ ha}^{-1}$) on watershed 1 was clearcut and removed by helicopter. Treatment of logging residues included lopping and scattering and some hand piling. Attempts were made to burn some of the piled slash in November 1972, but results were poor.

The following summer was hot and dry. On August 20, 1973, a wildfire started near the mouth of the Pine Creek drainage and burned 972 ha in a few hours, including both study watersheds. The fire burned very hot, consuming a large amount of fuel. Estimated fuel loading at the time of the fire was 202 Tonnes metric ha^{-1} on the clearcut watershed and 22 Tonnes metric ha^{-1} on the uncut watershed. The additional fuel on the logged watershed resulted from logging slash and caused a greater burn intensity on clearcut watershed 1 as compared to uncut watershed 4.

Most of the burned area was logged by helicopter during late summer and fall 1973 to salvage the standing timber killed by the fire. However, salvage logging was not done on the unlogged control watershed nor within a border strip at least 30 m wide surrounding both study watersheds in order to preserve as much of the original study design as possible, even though the trees were killed by the fire.

The original study was designed to determine the effects of clearcutting on hydrologic responses by using covariance analysis to compare data from the treated and control watersheds before and after logging. However, such an analysis was not possible because the fire destroyed the statistical control provided by the unlogged watershed. Alternative analysis techniques were applied, depending on the type of hydrologic data. Annual group comparisons were used to test for statistical differences between the two watersheds for data collected at multiple sites on each watershed. Data of this type included maximum snow water equivalent, snow ablation rate, and maximum and minimum levels of unsaturated soil moisture. Changes in average snow water equivalent were also evaluated by comparing data collected on the two study watersheds to independent snow course data with a double mass analysis. Changes in shortwave solar radiation reaching the ground in the spring were analyzed by comparing data collected in the open and on the clearcut watershed before and after logging. Changes in peak piezometric rise, peak piezometric storage in the subsurface flow zone, and volume of flow intercepted by the road cut slope were all evaluated by regression analysis, using either snow ablation rate or snow water equivalent as independent variables. Changes in either snow ablation or water equivalent predicted from independent analyses were then used in conjunction with the regression coefficients to predict changes in the corresponding dependent variables. A similar regression approach was used to evaluate changes in the peak rate of flow intercepted by the road cut, except the peak piezometric stor-

age in the subsurface flow zone was used as the independent variable.

Data Collection

An in-sloped logging road marks the lower boundary of both study watersheds. Road cut banks are high enough that bedrock is exposed across the entire width of both watersheds. Subsurface flow, emerging on the face of the road cut, runs down the granitic bedrock to a collection trough fastened to the bottom of the cut slope. Flows collected across the entire face of the watersheds (a distance of approximately 45 m on watershed 1 and 49 m on watershed 4) were carried in the troughs to small Parshall flumes where water-level recorders continuously measured flow. Collection troughs were covered to drain away rain and to help keep out debris. In addition, a metal cutoff wall that barely penetrated the soil surface was used to deflect surface flow into a separate measuring reservoir.

A recording rain gage, hygrothermograph, recording pyranometer, and anemometer were operated at a weather station adjacent to the watersheds. A modified version of the snow lysimeter described by Haupt [1969], using a circular plot with an area of 0.93 m^2 , was operated on each watershed to continuously measure outflow of water from the snowpack. Some weather data were also collected at the snow lysimeter site on watershed 1 by using a hygrothermograph and recording pyranometer both before and after clearcutting. Also, 52 snow stakes and 21 neutron access tubes for soil moisture determination were located in a grid pattern on the study watersheds. Finally, 25 crest gage piezometers were located in suspected water accumulation areas (Figure 1).

Snow water equivalent was measured at each snow stake at intervals of approximately 1 month throughout the winter and daily during active snowmelt, whenever possible. Also during active snowmelt, present and maximum water depths since the previous measurement were determined for each crest gage piezometer at least once during any day that snow surveys were conducted. Soil moisture was measured by using the neutron scattering technique at 30.5-cm intervals from 30 to 152 cm in depth. Measurements were made at the end of snowmelt (on or about May 15) and at approximately monthly intervals throughout the following summer and fall. Data collection was continued, except for minor interruptions, until the summer of 1975.

RESULTS AND DISCUSSION

Snow Accumulation

Annual maximum snow accumulation is the primary factor regulating the amount of subsurface outflow each year. Twenty-seven years of snow accumulation data are available from a standard snowcourse at Cozy Cove, a point about 14.5 km southeast of the study area, at an elevation approximately 100 m higher. A frequency analysis of the Cozy Cove data indicated that a good range of snow accumulations was sampled during the study, with an extremely high snowpack in 1971 and a low snowpack in 1973 (Table 1).

The average annual peak snow water equivalents for the study watershed are shown by year in Table 2. Each annual average represents 35 sample sites on watershed 1 and 17 on watershed 4. Annual group comparisons showed that the maximum snow water contents on the watersheds did not differ (95% level) in the three calibration years. There was a highly significant increase (99% level) in snow water content in 1973

TABLE 1. Amount and Probability of Occurrence of Maximum Snow Water Equivalents at Cozy Cove for the Years of Study

Year	Exceedence Probability	Maximum Water Equivalent, mm
1970	0.40	500
1971	0.01	721
1972	0.42	490
1973	0.89	277
1974	0.30	533
1975	0.28	538

following clearcut logging. Similar statistically significant increases (99% level) were found on the logged compared to the unlogged watershed in 1974 and 1975 after both drainages were burned. Thus the relative effects of logging on snow accumulation were manifest, regardless of the burning. The actual increased water contents amounted to 117, 150, and 160 mm in 1973, 1974, and 1975, respectively. These increases ranged from 35% to 57% and averaged 41% (Table 3).

The effects of disturbance on each individual watershed were evaluated by comparing the peak snow water contents on the study watersheds to the peak water equivalent on the Cozy Cove snow course via use of a double mass analysis (Figure 2). The logging effect is apparent for watershed 1, as indicated by the distinct change in slope in 1973. Burning appeared to have little influence on snow accumulation on the unlogged watershed, as evidenced by the lack of a distinct slope break between 1973 and 1974. There is a tendency for a downward trend in slope for the logged watershed after burning that suggests decreased snow accumulation. In spite of this, maximum water equivalents were still greater than those on the unlogged watershed.

Other studies suggest that openings cut in the forest stand tend to cause maximum amounts of increased snow accumulation when the opening site is approximately 2 to 3 times the height of the adjacent trees [Hoover and Shaw, 1962; Gary, 1974; Golding and Swanson, 1978]. Golding and Swanson found that average maximum snowpack water equivalent on forest stands in Alberta Canada, was increased by 45% for an opening 2 times as wide as the adjacent trees and 43% by an opening 3 times as wide. These results are close to the average of 41% increase found on the study area for the clearcut opening that was 2.7 times greater than the height of the adjacent trees.

Changes in maximum snow accumulation caused by forest cutting occur in response to (1) changes in winter snowmelt

rates, (2) reduced interception losses in the forest crowns, or (3) aerodynamic effects, including increased deposition within opening caused by discontinuities in the airflow across forest canopy and redistribution of deposited snow between forest opening and the adjacent stand. Data from the snow lysimeters showed only about 5% of the total melt occurring during the winter, either before or after logging, so this factor is unimportant. Also, all leaves on the trees and understory vegetation were killed by the fire on the uncut watershed, so interception losses were reduced. In spite of reduced interception there were no detectable increases in maximum snow water content on the unlogged watershed. On this basis, most of the change in maximum snow water equivalent on the logged watershed probably resulted from changes in the aerodynamics of the timber stand.†

Snowmelt Rates

Incoming shortwave solar radiation is the primary source of energy regulating spring snowmelt. A comparison of the data sets for the spring snowmelt before and after clearcutting shows that shortwave solar radiation input to the snow surface increased from about 100% to 375% after clearcutting, depending on cloudiness and sun altitude (Figure 3). Such a large increase in shortwave radiation suggests that snowmelt rates would probably increase after timber removal, especially during clear weather.

It was impossible to analyze the snow lysimeter data to evaluate effects of disturbance on snowmelt rates because of discontinuous records. However, ablation data from the snow stakes were useful. The average snow ablation rates from the time of maximum snow water accumulation until the time of disappearance of snow (or the last measurement date in a few cases) provide a good index of snowmelt (Figure 4). Mean ablation rates on the two watersheds did not differ (95% level) for each predisturbance year: 1970, 1971, and 1972. In 1973, clearcutting increased ablation rates (99% level) on the logged watershed an average of 2.5 mm day⁻¹ compared to the unlogged watershed. After the wildfire the ablation rates on the clearcut watershed still averaged 2.3 and 2.8 mm day⁻¹ greater (99% level) than rates on the uncut watershed in 1974 and 1975, respectively. Ablation rates on the clearcut watershed increased an average of 30% for the 3 years following both logging and burning (Table 3). There is no way to evaluate the effects of the fire on snowmelt rates on the unlogged watershed. However, based on the large, relatively consistent differences between ablation on the clearcut and uncut watersheds both before and after the wildfire, the effects appear to be minor.

TABLE 2. Annual Average Maximum Snow Water Equivalent for Study Watersheds

Year	Watershed 1, logged and burned, mm	Watershed 4, burned, mm	Difference 1-4	Statistical Test
1970	358	386	-28	N.S.D.*
1971	444	455	-10	N.S.D.
1972	396	348	+48	N.S.D.
<i>Cut November</i>				
1973	323	206	+117	***
<i>Burned August</i>				
1974	579	429	+150	**
1975	554	394	+160	**

*N.S.D.—No significant difference at 95% level.

†***—Significant difference at 99% level.

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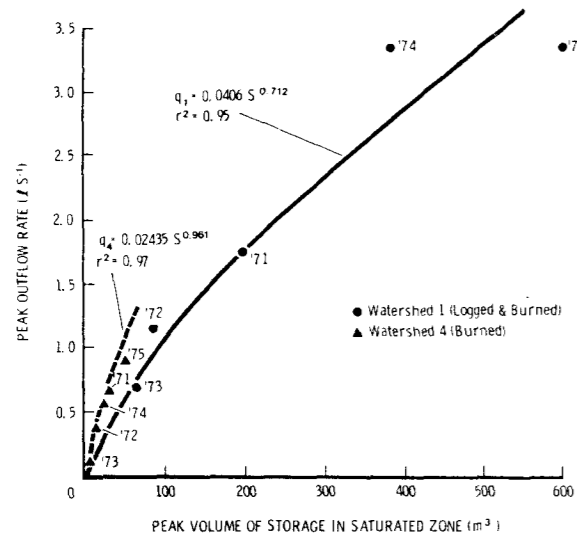


Fig. 9. Annual peak rate of outflow vs. peak storage in saturated zone.

ously, the potential for erosion damage is greatly enhanced when roads intercept the subsurface flow zone. Hazards are even further increased when the slopes above the roads are clearcut. In this case, flow volumes from subsurface flow interception may rise as high as 18 times those caused by precipitation falling directly on the road. Accompanying the increased volumes of flow are large increases in the peak subsurface flow rates as well.

CONCLUSIONS

The hydrologic responses to the clearcutting and wildfire impacts on the two study watersheds are summarized in Table 3. Three major groups of hydrologic processes were investigated: (1) snow accumulation and melt rates, (2) evapotranspiration, and (3) storage and outflow of water as saturated subsurface flow.

Clearcut logging alone caused large, statistically significant increases in all of the parameters used to index snow accumulation and melt rates the first snowmelt season after logging. Increases relative to the unlogged watershed continued to occur in the 2 years following wildfire. The 3-year average effects following disturbance on the logged and burned watershed showed a 41% increase in maximum snow water equivalent, a 100–375% increase in incoming shortwave solar radiation at the surface of the snowpack and a 30% increase in the snowpack ablation rate. Most of the increase in snow water equivalent was attributed to changes in the aerodynamics of the forest stand caused by the creation of the clearcut opening.

The wildfire may have increased snow accumulation and melt on the unlogged watershed as well. However, no good statistical control was available to evaluate the amount of increase. Slight increases in peak snow accumulation were suggested on the basis of a double mass analysis with an independent snow course, but amounts of change were inconclusive. Undoubtedly, increases occurred in the amount of incoming solar radiation reaching the snowpack, but not as much as on the logged watershed. The increased radiation load may have caused some acceleration of snowmelt, but amounts would have to be considerably less than those recorded on the clearcut watershed.

Evapotranspiration was reduced by logging, logging plus burning, and burning alone by 54 mm, 51 mm, and 79 mm,

respectively. The storage and outflow of water as saturated subsurface flow was also increased by logging and logging plus burning. Maximum piezometric levels showed the greatest average increase after disturbance amounting to 47%, compared to maximum piezometric storage, which was increased an average of 27% by disturbance. In response to increases in piezometric levels and total storage, the volume of subsurface flow intercepted by the road cut was increased 96% by logging and logging plus wildfire. This was accompanied by average increase in the peak rate of outflow of 27%.

Although snow accumulation and melt reacted differently after disturbance on the two watersheds, transpiration effects were similar, and if anything, they were greater on the unlogged watershed. Considering the much larger piezometric and subsurface flow responses on the logged watershed, it appears that factors influencing snow accumulation and melt, rather than reduced evapotranspiration, dominate the spring hydrologic performance of individual slopes in this area. This is partly because most of the soil moisture deficit caused by evapotranspiration is satisfied by late fall and early winter rains. This conclusion is reinforced by Nelson [1969], who reported that soil moisture contents in January had little influence on the volume of snowmelt runoff in Idaho.

Clearcut size is an important factor regulating both the total amount of snow accumulation and the rate of snowmelt. Since snow accumulation and melt rate were the major factors causing increased hydrologic responses in this study, it would be reasonable to adjust clearcutting sizes accordingly in areas where slope hydrologic performance is a concern. Silvicultural systems that use partial tree removal might also be considered especially where mass erosion problems exist.

For roads in midslope or lower locations, special design features should be included to accommodate additional flows caused by incision of the subsurface flow zone. This is especially critical when clearcut timber removal is anticipated above the road. Forest managers may want to consider avoiding clearcutting above roads in areas that are highly susceptible to road erosion. Likewise, road construction for timber salvage purposes in wildfire areas should be located on the upper portions of the burned area whenever possible.

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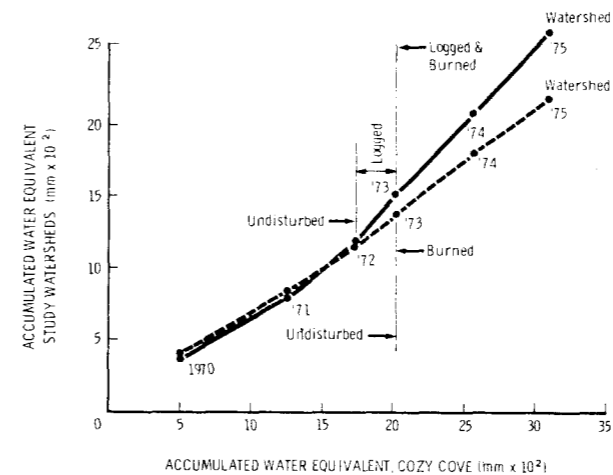


Fig. 2. Double mass analysis of annual maximum snow water equivalent on study watersheds vs. Cozy Cove.

Unsaturated Soil Water Content

Unsaturated soil moisture on the study area is typically at maximum during the spring and drops throughout the dry summer, primarily in response to evapotranspiration. Normally, minimum soil moisture contents occur during late summer or early fall. Average minimum moisture contents on the two watersheds ranged from 89 to 122 mm for the 3 years prior to disturbance (Figure 5). Soil moisture content in watershed 1 was not different (95% level) than that in watershed 4 for any of the years before logging. In 1973, minimum soil moisture levels on the unlogged watershed were similar to the previous years, whereas moisture levels on the logged area only dropped to 145 mm, representing a significant decrease (95% level) in evapotranspiration of 54 mm. Following wildfire, evapotranspiration was reduced on both watersheds so that there were again no significant differences (95% level) between minimum soil moisture contents for each of the two years sampled. Compared to predisturbance conditions, however, there were significant (95% level) increases on both watersheds. Watershed 1 increased from an average 117 mm for the 3-year predisturbance period to 168 mm for the 2 years following wildfire, and watershed 4 increased from 109 mm for the 3-year predisturbance period to 187 mm for the 2 years following wildfire (Table 3).

The reductions in evapotranspiration after burning are undoubtedly real because the fire reduced the leaf transpiring surface considerably on the unlogged watershed and possibly on the logged watershed as well. Also, the range in climatic conditions was quite similar for the summer evapotranspiration periods before and after burning. Finally, no differences (95% level) existed between average maximum water contents on the two watersheds for any of the years studied, either before or after disturbance.

Piezometric Response

Landslide hazard is directly proportional to the depth of the saturated zone relative to the soil depth [Swanston, 1967; Ward, 1976; Wu and Swanston, 1980]. Accordingly, the piezometer with the greatest water depth relative to the soil depth was selected to define the most probable point of failure in the slope. The peak piezometric rise at this point was then related to annual average snow ablation rate to show possible effects of disturbance (Figure 6). The well-defined relationship between

peak piezometric rise and ablation rates suggests no apparent effects of either logging or burning, even though effects might have been expected. For example, severe soil compaction caused by logging could increase piezometric levels because of reduced soil hydraulic conductivity. On the other hand, increased overland flow caused by soil water repellancy after burning might reduce piezometric levels. However, neither of these factors occurred on the study area. The helicopter logging operation caused almost no soil compaction, and no overland flow was observed during snowmelt.

The regression coefficients on Figure 6 are highly significant (99% level), and the r^2 values are high (0.94 and 0.95) so piezometric rise is closely associated with increasing ablation rates. For example, a 1.0 mm day^{-1} increase in average ablation rates caused maximum piezometric levels to increase 8.7 and 7.4 cm on watersheds 1 and 4, respectively. The larger slope and intercept for watershed 1 probably reflect the greater drainage area above the test piezometer compared to the test piezometer on watershed 4.

The regression relationship can be used to estimate the effects of logging on peak piezometric rise because logging increased ablation rates (99% level). For example, ablation rates were increased on the logged watershed an average of 2.5, 2.3, and 2.8 mm day^{-1} for the postlogging years of 1973, 1974, and 1975. Based on the regression coefficient for watershed 1 of 0.087, these ablation increases represent respective increases of 0.22, 0.20, and 0.24 m in maximum piezometric levels. On the average the maximum piezometric level was increased 47% by logging (Table 3).

Overland flow with increased potential for surface erosion can occur during snowmelt if piezometric surfaces rise to the soil surface. This almost occurred in this study in 1975 when the water level reached to within 1 cm of the soil surface in the test piezometer on watershed 1 and could easily occur elsewhere. The most important concern with increased piezometric levels on steep slopes is increased landslide hazards. Coupled with reduced cohesive strength resulting from the postlogging decay of tree roots, increased piezometric depths can seriously increase landslides. In fact, some small mass failures did occur on the logged watershed during this study [Gray and Megahan, 1981].

A companion analysis was made to evaluate the change in

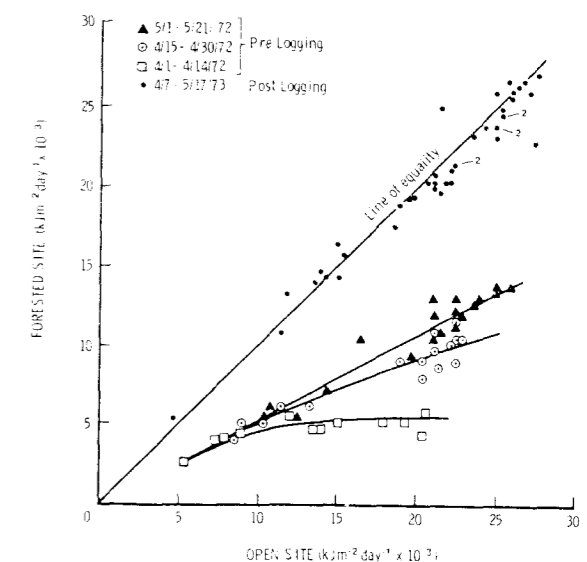


Fig. 3. Incoming shortwave solar radiation on forested and open site.

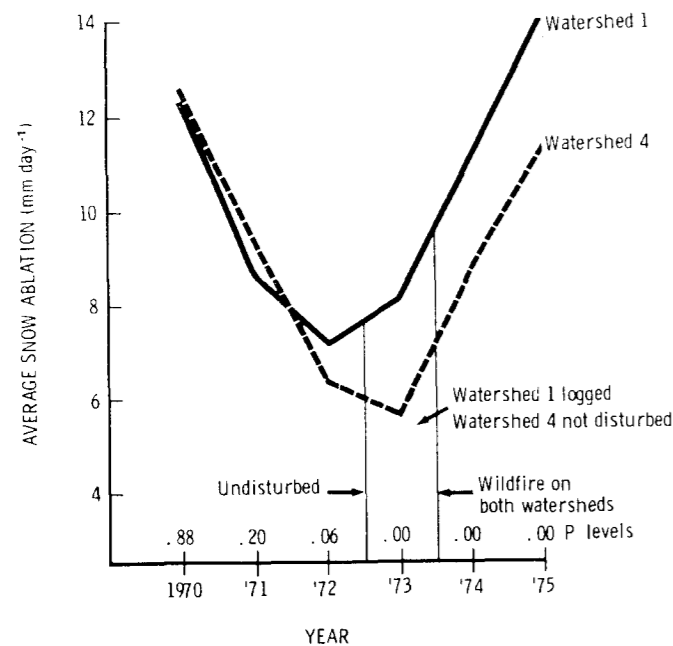


Fig. 4. Average snow ablation rate from time of maximum accumulation.

documented changes in ablation rate caused by logging and the regression coefficient for watershed 1 (Figure 7), logging creased total piezometric storage by 66, 68, and 84 m³ in 1974, and 1975, respectively. This amounts to an average crease of 27% (Table 3).

Volume and Rate of Subsurface Flow Runoff

Overland flow did not occur at any time during predisturbance years on either watershed. Also, no overland flow occurred on watershed 1 from the time of logging in November 1972 to the time of the wildfire in August 1973. Overland flow did occur during a few high-intensity storms in late summer and fall 1973, following burning, and was limited to the logged watershed. Overland flow was indexed by the dimensions of all rills caused by the flow; actual measurements of the flow itself were impossible because the collection systems were destroyed by fire. There was no overland flow, as evidenced by changes in rill dimensions by the second year after burning, probably because of a combination of limited high-intensity storm activity and vegetation regrowth [Megahan and Molitor, 1975].

By far the largest impact of disturbance was manifest as increased subsurface outflow. This can be shown by plotting the volume of annual subsurface flow intercepted by the road cut on each watershed against the corresponding annual peak snow water equivalent (Figure 8). The two variables are closely related, as evidenced by an *r*² value of 0.92 and a highly significant (99% level) regression coefficient. Both watersheds appear to be functioning similarly, as indicated by the overlapping scatter of the data points. Also, the lack of divergence of the data sets before and after disturbance suggests the logging and burning did not affect the relationship. This latter conclusion is further substantiated by the fact that no postdisturbance overland flow was observed on either watershed during snowmelt. However, the clearcutting did cause increases in the peak snow water equivalent (95% level) of all the postlogging snowmelt seasons in the amount of 117, 150, and 160 mm in 1973, 1974, and 1975 (Table 3), respectively. Based on the regression coefficient of 0.8 (Figure 8), the increased snow water equivalent increased subsurface flow runoff by 74, 120, and 128 mm for 1973, 1974, and 1975, respectively. This represents an average increase of 96% in the volume of subsurface flow runoff for the three years following logging and burning (Table 3).

Increased volumes of runoff were accompanied by increases

the maximum volume of subsurface flow water stored in the slope by using data collected on the date with the greatest average piezometric depth. The subsurface volume was determined by multiplying the depth of the saturated zone at each piezometer site by the area represented by each site determined from a Thiessen net and by the average porosity for the saturated zone, then summing for the total number of piezometers in each watershed. The data are summarized in Figure 7. Similar to the relationship developed between peak piezometric rise and ablation, there was no apparent effect of either cutting or burning on the relationship between peak piezometric storage and ablation. The regression coefficients between piezometric storage and average ablation rate were statistically significant at the 99% level of confidence and *r*² values were 0.96 and 0.97. Differences in the regression coefficients probably reflect the differences in drainage areas for the two watersheds. Using the

TABLE 3. Amount of Change in Hydrologic Components After Logging and Wildfire

Hydrologic Component	Watershed 1, logged and burned			Average Increase, %	Watershed 4, burned		Average Increase, %
	1973	1974	1975		1974	1975	
Maximum snow water equivalent, mm	+117**	+150**	+160**	+41**	No apparent change		—
Incoming shortwave solar radiation, kJm ⁻² day ⁻¹ *	From 2 to 16 × 10 ⁻³			+100 to +375	—	Unknown	—
Snow ablation rate, mm day ⁻¹ †	+2.5**	+2.3**	+2.8**	+30**	—	Unknown	—
Annual minimum unsaturated soil water, mm‡	+54§	+51§	—	+44§	—	+79§	+72§
Maximum piezometric rise, m*	+0.22	+0.20	+0.24	+47	—	Unknown	—
Maximum piezometric storage, m ³ ¶	+66	+68	+84	+27	—	Unknown	—
Volume of subsurface flow, mm*	74	120	128	+96	—	Unknown	—
Peak rate of subsurface flow, l s ⁻¹ ¶	+0.68	+0.90	0	+27	—	Unknown	—

*Increases on watershed 1 are absolute and vary with sun angle and cloudiness. Increases undoubtedly occurred on watershed 4 as well but not as high as on watershed 1—actual amount of increase on watershed 4 unknown.

†Increases shown for watershed 1 are based on a comparison to rate measured on watershed 4. Some smaller increases probably occurred watershed 4 as well, but the amounts are unknown.

‡Increase for watershed 1 is relative to watershed 4 in 1973. Increases for 1974 and 1975 are compared to average values for 1970, 1971, and 1972.

§Meaningful statistical test not possible.

¶Indicates difference significant at the 95% level.

**Indicates difference significant at the 99% level.

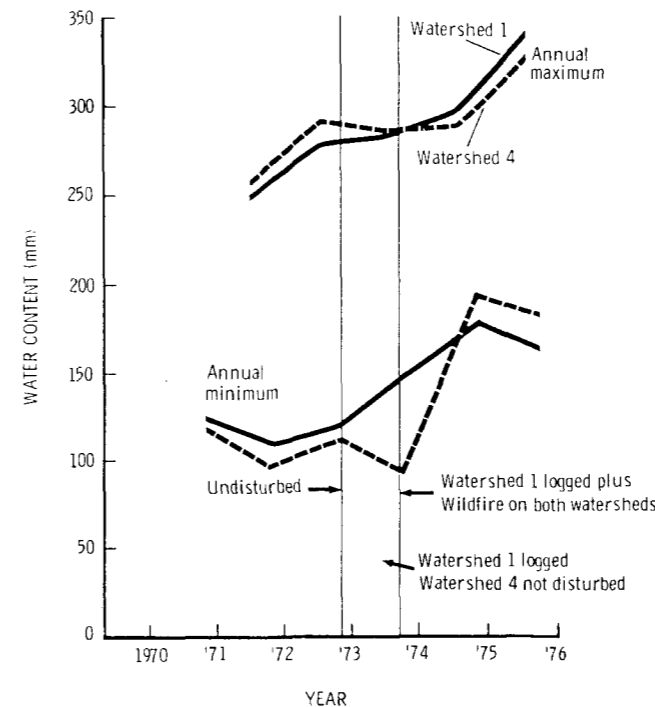


Fig. 5. Annual maximum and minimum soil water content for 30–152 cm depth.

in the peak rate of subsurface flow runoff. This was determined by relating the peak rate of subsurface flow intercepted by the road cuts to the peak volume of subsurface flow water stored in the saturated zone for each watershed (Figure 9). The relationships should remain unchanged before and after disturbance unless the logging and fire changed the hydraulic conductivity in the subsurface flow zone. There is no reason fire would cause a change deep enough to influence the subsurface flow zone, nor would the minimal soil disturbance associated with helicopter logging. Furthermore, the plotted data show no pre- and post-disturbance trends. Thus it is valid to group both the pre- and post-disturbance data in the regression analysis. Power functions were used for the regression analysis of the two data sets because they minimized the standard error and forced the relationships through the origin. A relatively good fit was obtained with *r*² values of 0.97 and 0.94 and highly significant regression coefficients (0.99 level). A covariance analysis of the two relationships showed that the two fitted curves were different. The greater exponent for watershed 4 is due in part to the

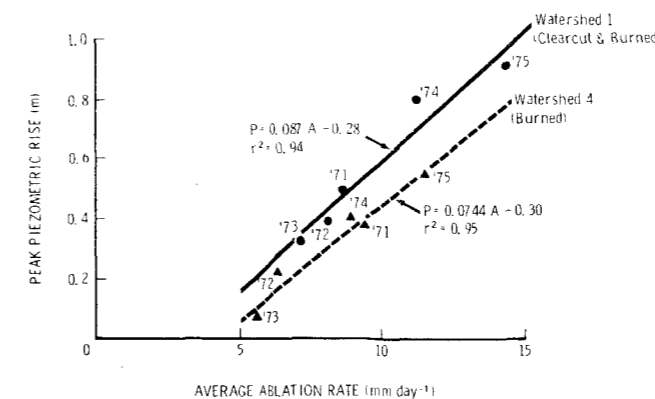


Fig. 6. Peak piezometric rise vs. average ablation rate.

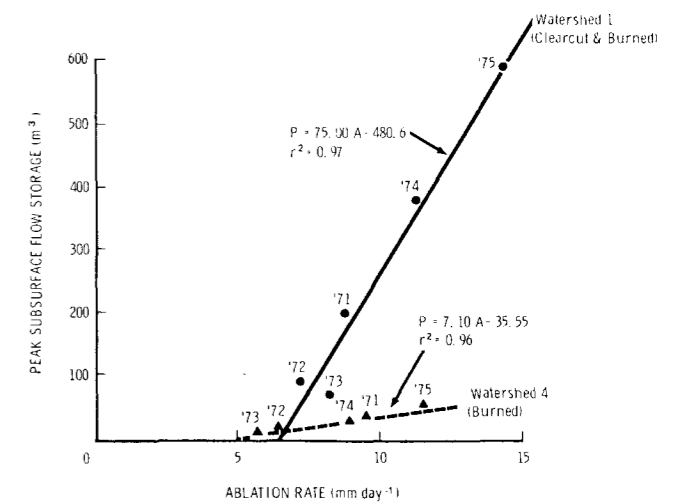


Fig. 7. Total piezometric storage vs. average ablation rate.

steeper average hydraulic gradient as compared to watershed 1 (0.62 vs. 0.52).

Using the estimated change in peak saturated water stored in the subsurface flow zone derived from Figure 7 with the relationship on Figure 9, it is possible to estimate the changes in peak flows caused by logging. Estimated increases in peak storage attributable to logging amounted to 66, 68, and 84 m³ for 1973, 1974, and 1975, respectively. By subtracting these amounts from the actual storages measured in the postlogging years and entering the remainders into the equation on Figure 9, the estimated peak flow rates without logging are obtained. The estimated and measured peak flows are then compared. Using this procedure, the respective increases in peak flow amount to 0.68, 0.90, and 0.00 l s⁻¹ in 1973, 1974, and 1975, respectively. The zero value in 1975 resulted from the deviation from the regression line, which is greater than the change in storage for that year. The zero value in 1975 is counterbalanced by the 1974 value, which is almost the same distance to the other side of the regression line. On the average, clearcutting caused a 27% increase in the peak rate of subsurface flow intercepted by the road cut (Table 3).

Roads have consistently been a primary source of erosion and sedimentation from forest management activities in mountainous lands [Rice et al., 1972]. Megahan [1972] estimated that subsurface flow runoff from forested slopes intercepted by road cuts was about 7 times greater than runoff caused by precipitation falling directly on the road surface. Almost all this water must run off as overland flow and represents a potential for increased erosion within and below the road prism. Obvi-

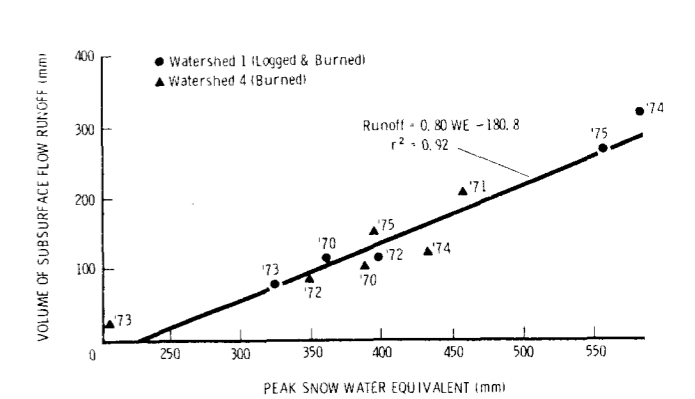


Fig. 8. Total subsurface runoff vs. peak snow water equivalent.