Snowmelt and Logging Influence on Piezometric Levels in Steep Forested Watersheds in Idaho

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ABSTRACT

This study was designed to evaluate the effects of clear-cut logging on piezometric levels caused by subsurface flow on steep granitic slopes in the mountains of Idaho. Data were collected on control and treated watersheds both before and after logging. Wildfire burned over both study watersheds less than 1 year after logging. Data collection included a complete weather station adjacent to the study watersheds plus two snow lysimeters, a sample grid of 52 snow stakes for measuring snow-water equivalent, and 25 crest gauge piezometers located on the study watersheds. Snowmelt was the primary factor influencing piezometric levels. Instantaneous and mean daily snowmelt rates were poor predictors of peak levels. Average ablation rates from the time of maximum snow accumulation to the time of disappearance of the snowpack were closely correlated with maximum and average piezometric levels. Logging influenced levels by increasing snow accumulation and melt rates and by changing snow distribution. Maximum and average piezometric levels were increased 41 and 68 percent, respectively, by logging. The data suggest that the frequency of occurrence of maximum levels was increased by up to 10 times by the clear-cut logging activities.

Piezometric levels are unique at many locations in mountainous areas because they are caused by snowmelt rather than rainfall and are not the result of fluctuations in permanent groundwater levels. Rather, positive pore-water pressures commonly result from subsurface flow. Chow (1, p.14-2) defined subsurface flow as "runoff caused by precipitation that infiltrates the surface soil and moves laterally through the upper soil horizon toward the streams as ephemeral, shallow, perched groundwater above the main groundwater level."

Whipkey (2) 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 km^2) 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 percent 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, which rapidly infiltrates and flows downward to the bedrock surface. Continued inflow of water creates a saturated layer at the bedrock surface and causes subsurface flow downslope along this surface. Infrequent large cyclonic storms, sometimes coupled with snowmelt, may also generate subsurface flows in the area.

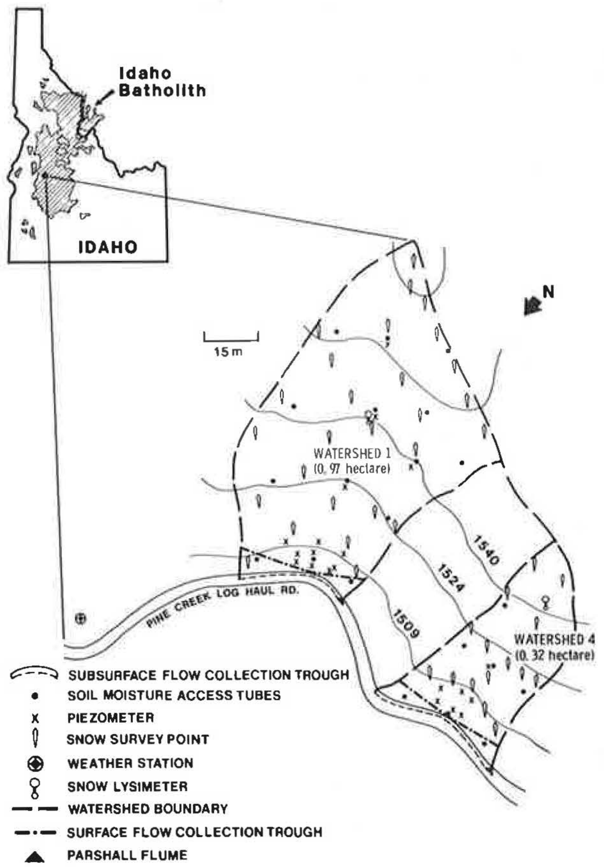

FIGURE 1 Location map and detail of the study area.

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 (3). 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. If timber harvest increases total runoff but not overland flow, then deep groundwater flow or shallow subsurface flow in the soil zone or both must increase.

The depth of the zone of soil saturation is a critical factor regulating slope stability (4-6). Thus, slope stability may decrease in response to increased subsurface flow after logging. Loss of root strength after logging also contributes to increased landslide activity (7;8;9,pp.343-361). 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 following logging in mountainous areas (10). Megahan et al. (11,pp.226-239) found that landslide activity is accelerated following timber removal in the mountains of Idaho. Although root strength changes following timber removal have been documented, the effects of timber removal on piezometric response caused by subsurface flow have not been investigated.

In this study it was sought to determine how piezometric levels caused by subsurface flow vary under rainfall and snowmelt conditions both before and after timber removal by clear-cut logging. Less than 1 year after the logging, wildfire caused an expansion of the study objectives to evaluate the effects of burning as well.

STUDY AREA

The two study watersheds 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 are 0.97 ha (watershed 1) and 0.32 ha (watershed 4) in size and average about 1530 m in elevation. They 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 the study watersheds.

Before clear-cut 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 understory vegetation was necessary. The forest habitat is classified as Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) and Ninebark (*Physocarpus malvaceus* [Greene] Kuntze) (12). Tree cover consisted of a mature stand of ponderosa pine (*Pinus ponderosa* Laws.) averaging 65 cm in diameter at breast height (d.b.h.) and lesser amounts of second-growth Douglas fir averaging about 35 cm d.b.h. Predisturbance tree crown cover averaged 43 and 63 percent on the uncut and clear-cut watersheds, respectively.

Slope gradients range from 35 to more than 70 percent and have aspects 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 (13). 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} (unpublished data), whereas the saturated hydraulic conductivity of bedrock similar to that on the study area averages only about 0.007 cm min^{-1} (14).

Annual precipitation at the study area averages approximately 890 mm. Summers are hot and dry. Most precipitation occurs during the winter as snowfall. The maximum snowpack averages about 1.5 m deep and contains 360 mm of water equivalent. The spring snowmelt period averages about 6 weeks with maximum daily melt rates up to 66 mm.

STUDY DESIGN AND DATA COLLECTION

The original study design was a paired-watershed approach with calibration from 1970 to 1972. The effects of clear-cutting watershed 1 in 1972 were to be monitored from 1973 to 1975 and compared with the control watershed 4. Timber harvest activities were deliberately scheduled for late fall 1972 when both watersheds had their annual minimum soil moisture content. Transpiration during the subsequent winter and spring was minimal compared with that during the late spring to early fall growing period. Therefore, differences in hydrologic responses in spring 1973 were largely caused by 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 m^3 ha^{-1}) on watershed 1 was clear-cut 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 in a few hours burned 972 ha, 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 tons ha^{-1} on the clear-cut watershed and 22 tons ha^{-1} on the uncut watershed. The additional fuel on the logged watershed resulted from logging slash and caused a greater burn intensity on the clear-cut watershed 1 as compared with that on the 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, to preserve as much of the original study design as possible, even though the trees were killed by the fire, salvage logging was not done on the unlogged control watershed nor within a border strip at least 30 m wide surrounding both study watersheds.

A recording rain gauge, 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 (15) that used 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 clear-cutting. Also, 52 snow stakes were located in a grid pattern on the study watersheds. Finally, 25 crest gauge piezometers were located in suspected water-accumulation areas in each watershed, 14 in watershed 1 and 11 in watershed 4 (Figure 1).

Piezometer holes were installed vertically by hand augering through the soil and at least 10 cm into the underlying weathered rock. Piezometers consisted of 2.5-cm pipe with perforations extending about 20 cm above the bedrock surface. Bentonite seals at the soil surface and above the top of the perforations prevented water inflow from above. Total soil depth at the piezometers ranged from 46 to 119 cm and averaged 77 cm. Only nine and eight piezometers were available throughout the study on watersheds 1 and 4, respectively; the rest were lost in small slope failures along the road cut.

Snow-water equivalent was measured at each snow stake at intervals of approximately 1 month throughout the winter whenever possible and daily during active snowmelt. Also during active snowmelt, each crest gauge piezometer was read at least once during any day that snow surveys were conducted. Data collection was continued, except for minor interruptions, until the summer of 1975.

RESULTS AND DISCUSSION

Piezometric Response

Crest gauge piezometers provide two values at each reading: the level at the time of the reading and the maximum level since the last reading. Only maximum piezometric-level data are presented in this report. Piezometric responses caused by rainfall occurred only once during the 5-year study. A large rainstorm in fall 1973 preceded by a series of smaller storms caused some minor subsurface flow. Vegetation removal by logging the previous fall and wildfire during the previous summer undoubtedly contributed to the piezometric responses because of increased soil moisture levels at the start of the storm events.

By far the greatest piezometric responses were caused by snowmelt during spring. Following a period of initial recharge, piezometric levels might be expected to relate closely to the amount of water supplied to the slope from the melting snowpack. Outflow of water from the snowpack includes water supplied by snowmelt plus drainage of rainwater through the pack. The snow lysimeter data provide an excellent point measurement of the outflow of water from the snowpack. A time plot of the outflow for May 9 and 10, 1972, is shown in Figure 2 in relation

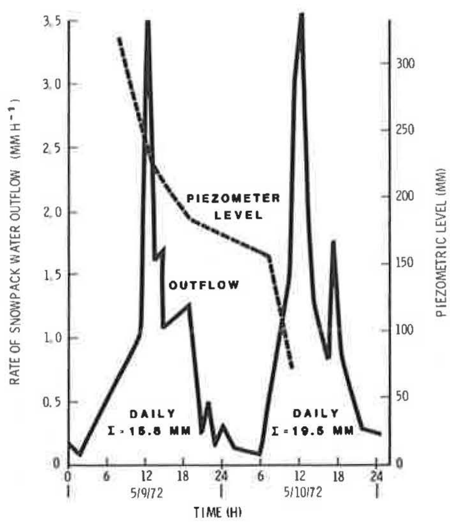

FIGURE 2 Instantaneous rate of water outflow from snowpack compared with water levels in piezometer 5 on logged watershed.

to the maximum levels recorded in piezometer 5 on the logged watershed. Piezometer 5 (total soil depth of 0.91 m) was selected because it consistently had the highest levels relative to soil depth of all piezometers sampled and thus was the most probable point of slope failure (assuming homogeneous conditions throughout). The period shown in Figure 2 represents the 2 days immediately after the time of peak piezometric rise for the year at this site. Note the extreme fluctuation in snowmelt outflow caused entirely by fluctuations in the energy available for snowmelt at the site; there was no rainfall during these 2 days. Unlike in continuous recordings, in this study piezometric levels based on crest gauge readings masked much of the variation. Even so, there is a continuous downward trend in piezometric levels in spite of extremely variable rates of water inflow. Obviously, short-term water inflow data of this type are not appropriate for estimating piezometric responses because of attenuation of levels caused by soil water storage.

Although providing an excellent record of water inflow to the snowpack, snow lysimeter data constitute a point sample within the watershed and thus may be a poor indicator of average watershed inflow rates. In addition, snow lysimeter data are expensive and exist at only a few specialized research sites. However, snow survey data giving the total water equivalent for the snowpack are common at many locations and are cheap and easy to obtain. Periodic comparison of the amount of water equivalent in the snowpack from the time of maximum snow accumulation to the time of disappearance of the pack provides an alternative to snow lysimeter data. Measurements of the rate of disappearance of the snowpack (called ablation) are not equivalent to data obtained from a snow lysimeter because it is impossible to account for evaporation and drainage of rainwater. In spite of these limitations, snow ablation rate data provide a good index of snowmelt rates.

In Figure 3, mean daily snow ablation rates collected in 1972 are plotted along with mean daily piezometric levels for piezometer 5 on the logged watershed. Spring 1972 was typical of the patterns of snow ablation and piezometric rises on the study watersheds. Relatively slow melt early in the season (totaling 250 mm by May 2) helped build up soil moisture levels. Average rates accelerated in early May, allowing for a relatively rapid increase in piezometric levels. Peak levels occurred on May 8 about 4 days after the occurrence of the peak ablation rate. Although mean daily ablation rates are more closely correlated to piezometric response than were instantaneous snowmelt outflow rates, ablation rates still do not provide a good prediction of peak piezometric rise, again because of soil moisture storage effects.

A more gross average of snowmelt, consisting of average snow ablation rate for the entire snowmelt season, was used to better account for storage effects. These values provided much better predictions of both maximum and average piezometric levels relative to soil depth on both watersheds (Figure 4). The maximum value is for the individual piezometer with the greatest level at the time of peak response. This was piezometer 5 on the logged watershed 1 and piezometer 3 (total soil depth 1.12 m) on the unlogged watershed 4. The average values repre-

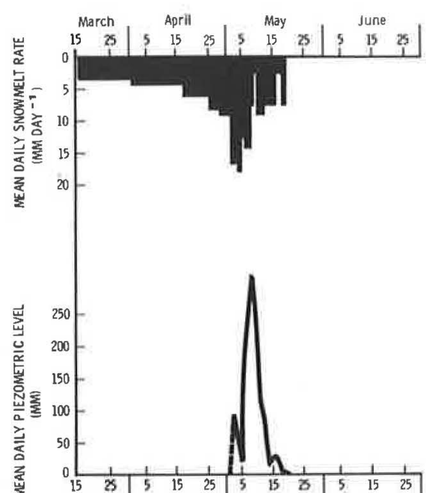

FIGURE 3 Mean daily ablation rate in relation to mean daily piezometric level in piezometer 5 on logged watershed for 1972.

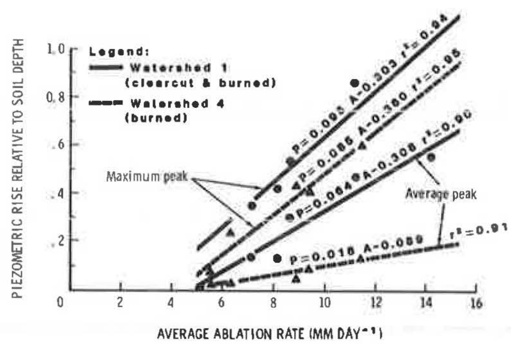

FIGURE 4 Peak relative piezometric level in relation to average ablation rate.

sent the mean level for all piezometers on each watershed at the time of peak response. All regressions are statistically significant (at the 99 percent level for piezometers with the highest response and at the 95 percent level for the average of all of them) and the r^2-values (ranging from 0.90 to 0.95) are relatively high; thus piezometric rise is closely associated with increasing ablation rates. For example, an increase in average ablation rate of 1 mm per day causes an average increase in the maximum level of groundwater depth relative to soil depth of 9 percent on the two study watersheds. All piezometers were sensitive to changes in ablation rate as indicated by the curves for the average responses. The higher responses on Figure 4 for watershed 1 compared with those for watershed 4 probably reflect the greater drainage area above the piezometers on watershed 1 relative to watershed 4.

Overland flow with increased potential for surface erosion can occur during snowmelt if piezometric levels rise to the soil surface. This almost occurred in this study in 1975 when the relative water level reached 0.98 at piezometer 5 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 levels can seriously increase landslides. In fact, some small mass failures did occur on the logged watershed during this study (10).

Snow Accumulation

Table 1 shows the annual average levels of snow-water equivalent for the study watersheds. Each annual average represents 35 sample sites on watershed 1 and 17 sites on watershed 4. Annual group comparisons showed that the maximum snow-water content on the watersheds did not differ (95 percent level) in the three calibration years. There was a highly significant increase (99 percent level) in snow-water content in 1973 following clear-cut logging on watershed 1. Similar statistically significant increases (99 percent level) were found on the logged compared with the unlogged watershed in 1974 and 1975, respectively. These increases ranged from 35 to 57 percent and averaged 41 percent.

TABLE 1 Annual Average Levels of Snow-Water Equivalent for Study Watersheds

Year	Snow-Water Equivalent by Watershed (mm) Watershed 1 (logged and burned)	Watershed 4 (burned)	Difference (1 − 4)	Statistical Test
1970	358	386	−28	NSD
1971	444	455	−10	NSD
1972[a]	396	348	+48	NSD
1973[b]	323	206	+117	SD
1974	579	429	+150	SD
1975	554	394	+160	SD

Note: NSD = no significant difference at 95 percent level; SD = significant difference at 99 percent level.
[a]Watershed 1 clear-cut in November.
[b]Both watersheds burned in August.

Double-mass analysis (16) was used to evaluate the effects of disturbance on each individual watershed by comparing the peak snow-water equivalents on the study watersheds to the peak water equivalent on a nearby undisturbed snow course (Cozy Cove) (Figure 5). 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 shown by the lack of a distinct slope break between 1973 and 1974. A tendency for a downward trend in slope for the logged watershed following burning suggests decreased snow accumulation. In spite of this, maximum water equivalents were still greater than those on the unlogged watershed.

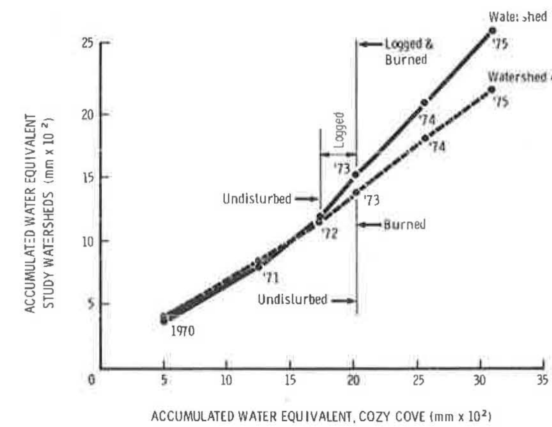

FIGURE 5 Comparison of accumulated peak snow-water equivalents on study watersheds to an undisturbed snow course by years.

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 two to three times the height of the adjacent trees (17,pp.246-252;18;19). Golding and Swanson (19) found that average maximum snowpack-water equivalent on forest stands in Alberta, Canada, was increased 45 percent for an opening two times as wide as the adjacent trees and 43 percent by an opening three times as wide. These results are close to the average of 41 percent increase found on the study area for the clear-cut 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 (a) change in winter snowmelt rates, (b) reduced interception losses in the forest crowns, or (c) aerodynamic effects including increased deposition within the opening caused by discontinuities in the airflow across the forest canopy and redistribution of deposited snow between the forest opening and the adjacent stand. Data from the snow lysimeters showed only about 5 percent of the total melt occurring during the winter either before or after logging, so factor a 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 content on the logged watershed probably resulted from change in the aerodynamics of the timber stand.

Snowmelt Rates

The average snow ablation rates from the time of maximum snow-water accumulation until the disappearance of snow (or the last measurement data in a few cases) provide a good index of snowmelt (Figure 6).

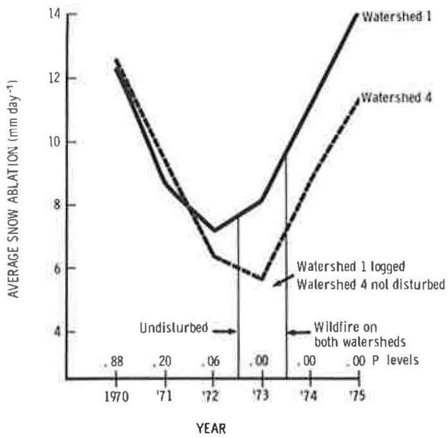

FIGURE 6 Average snow ablation rate from time of maximum accumulation by years.

Mean rates on the two watersheds did not differ (95 percent level) for each predisturbance year: 1970, 1971, and 1972. In 1973, clear-cutting increased ablation rates (99 percent level) on the logged watershed an average of 2.5 mm day^{-1} compared with those on the unlogged watershed. After the wildfire, the rates on the clear-cut watershed still averaged 2.3 and 2.8 mm day^{-1} greater (99 percent level) than rates on the uncut watershed in 1974 and 1975, respectively. Rates on the clear-cut watershed increased an average of 30 percent for the 3 years following both logging and burning. 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 clear-cut and uncut watersheds both before and after the wildfire, the effects appear to be minor.

Snow Distribution

Changes in the aerodynamics of a forest stand influenced snow distribution and contributed to increases in total snow accumulation. A three-dimensional fit of the water-equivalent values on watershed 1 taken from the network of snow stakes illustrates the change (Figures 7-9).

Each year before the disturbance, distribution of snowpack water equivalents was variable primarily because of the variegated timber cover. The water-equivalent distribution during 1972 is typical of the patterns on the clear-cut watershed before the disturbance (Figure 7). At the time of maximum accumulation, zones of high water storage were apparent on the upper and lower portions of the south side of the drainage and on the northwest side of the basin. A shallow zone separated the drift areas on the south side of the drainage and also occurred through the center and east side. Melting progressed nonuniformly so that most of the accumulation on the south side melted first, with minimal melt on the lower west side and center of the basin. After logging in

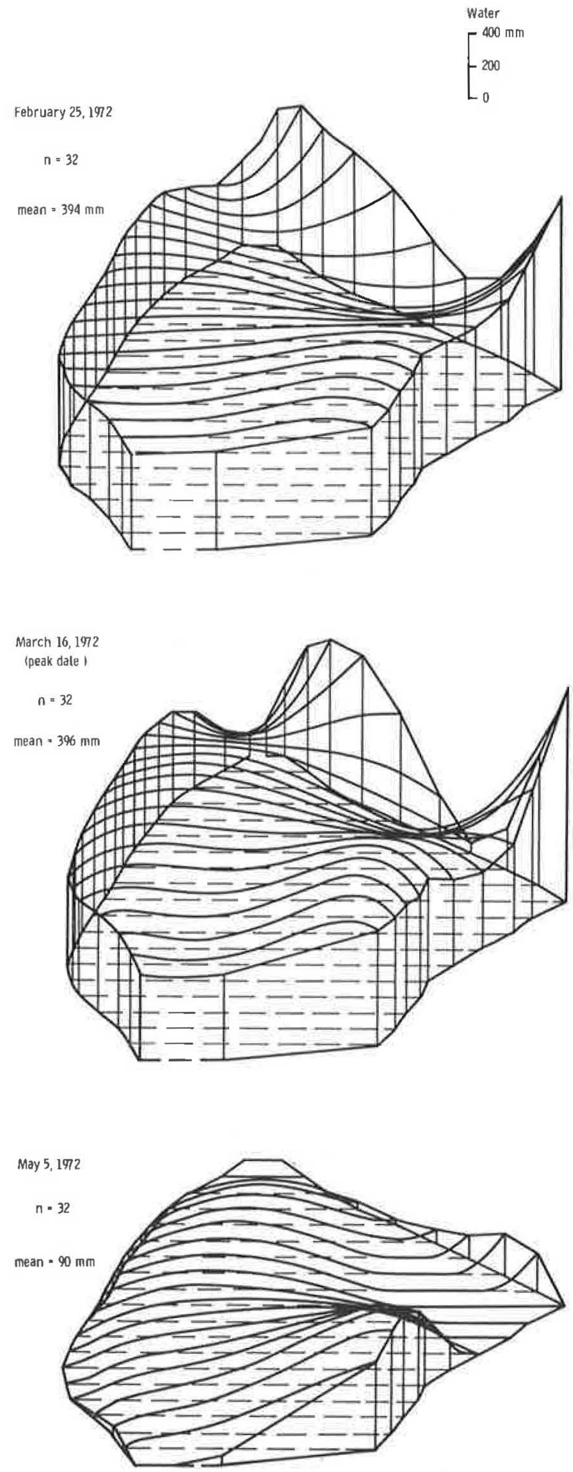

FIGURE 7 Snow distribution on clear-cut watershed before logging.

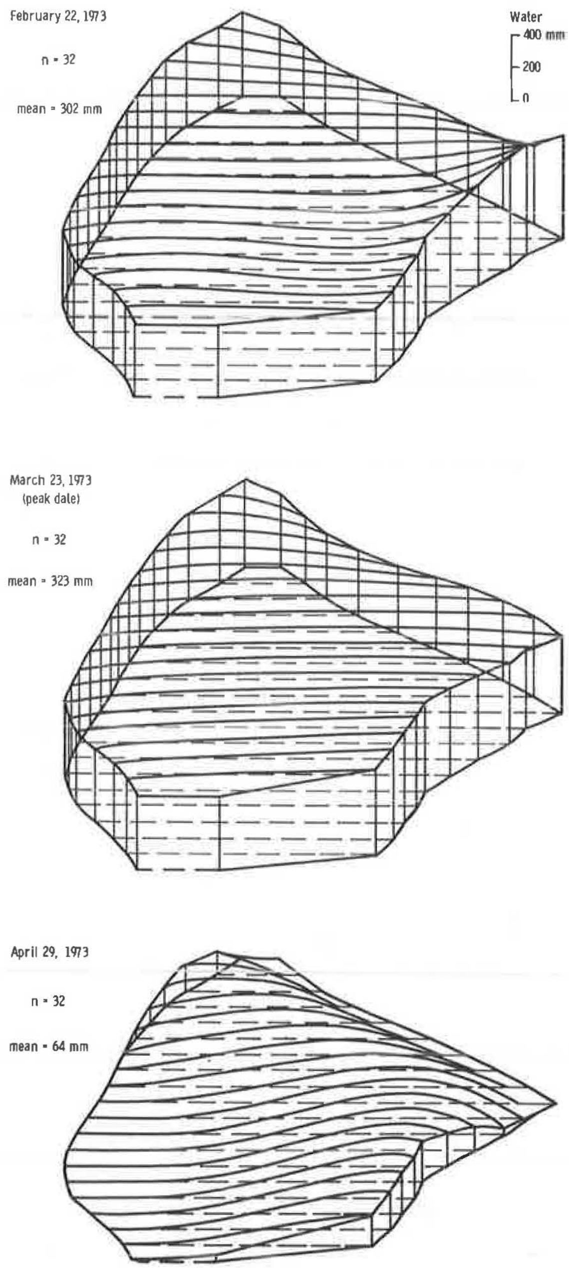

FIGURE 8 Snow distribution on clear-cut watershed after logging.

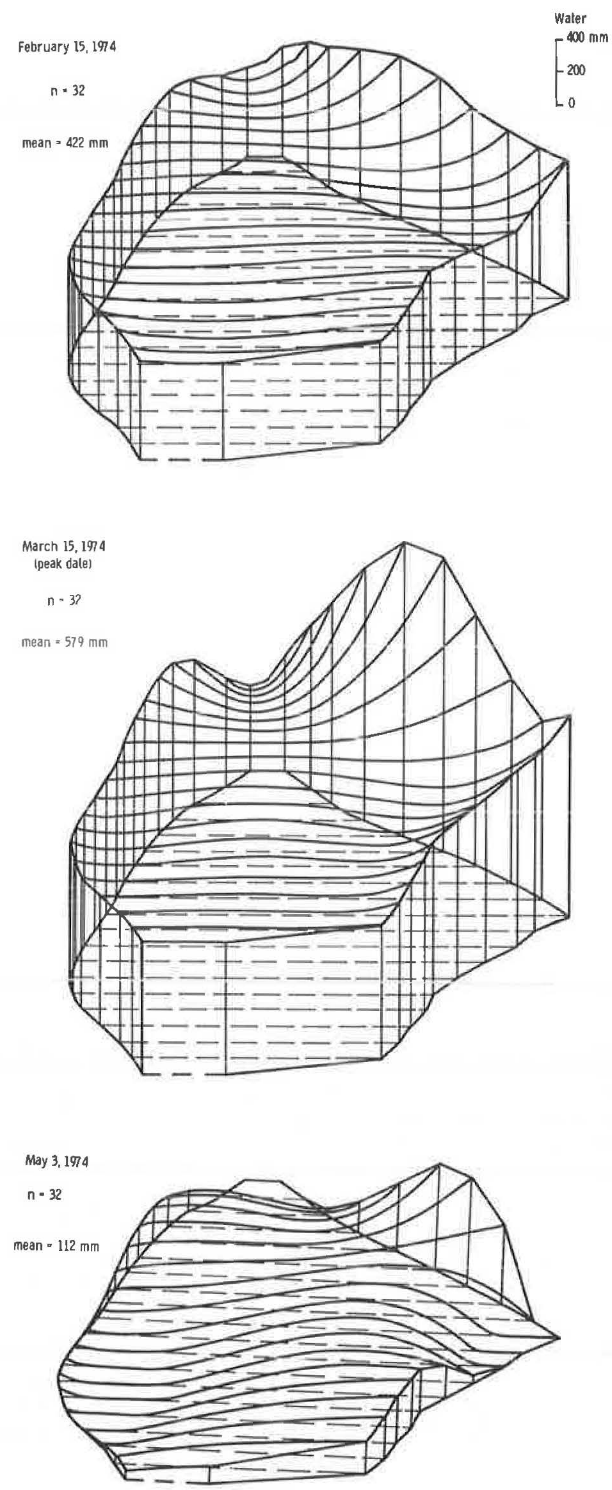

FIGURE 9 Snow distribution on clear-cut watershed after logging and burning.

1973, snow-water accumulation was quite uniform over the basin, with melt progressing from both the north and south sides of the basin toward the center (Figure 8). The wildfire caused a major change in snow-water distribution in 1974 and 1975. A single major drift area occurred on the south side of the basin with smaller drifts on the east and west sides. Melt progressed fairly uniformly over the watershed so that the early accumulations were still apparent late in the melt season (Figure 9). A similar analysis on the burned-only watershed showed no trends in snow distribution before and after burning.

The network of piezometers on the study watersheds was not dense enough to detect changes in piezometric levels caused by variations in snow distribution before and after the disturbance. However, major differences in maximum water equivalents throughout the watershed are apparent in Figures 7 and 9 with maximum water equivalents at individual sites varying by 100 percent or more. Thus, total inflow at a given site could be doubled just by changes in snow distribution leading to localized increases in piezometric levels and accompanying chances for slope failure.

Effects of Vegetative Removal

The regression relationship shown in Figure 4 can be used to estimate the effects of logging on peak piezometric rise because logging caused statistically significant increases in ablation. For example, ablation rates were increased in 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, respectively, compared with those on the unlogged watershed. This represents a 30 percent increase in average rates caused by logging. Based on the regression coefficient of 0.95 for the piezometer with the maximum level on watershed 1, these ablation increases represent respective increases of 0.24, 0.22, and 0.27 in relative piezometric height for an average increase of 41 percent. Similarly, average piezometric heights on the logged watershed were increased by 0.16, 0.15, and 0.18 in relative piezometric levels for an average increase of 68 percent.

These data make it possible to estimate the effects of timber removal on the probability of peak piezometric levels. For example, the maximum levels relative to soil depth on watershed 1 for 1973, 1974, and 1975 would have been 0.18, 0.65, and 0.72, respectively, if timber had remained undisturbed. If these data are combined with the data for the two additional years before the disturbance, the probability of piezometric levels for undisturbed conditions can be estimated. The five data points were plotted on normal probability paper by using the Hazen procedure (20) for determining plotting position. A curve was fitted to the data by using linear least squares (Figure 10). Obviously 5 years of data

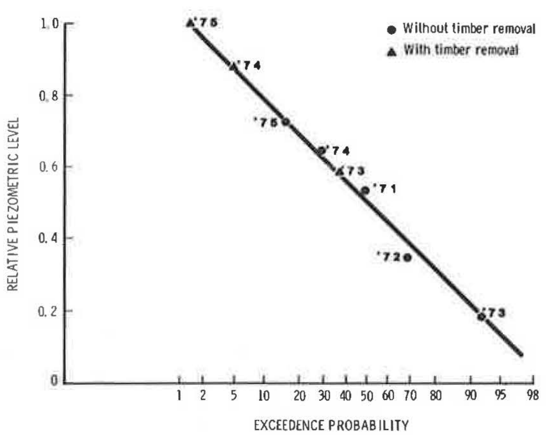

FIGURE 10 Probability of relative piezometric level on clear-cut watershed before and after timber removal.

are not adequate for accurate frequency analysis. However, the approach is useful for illustration purposes. For example, by using the fitted curve, the probability of occurrence of the peak piezometric level in 1975 would have been 0.17 for undisturbed conditions. Thus, levels of this magnitude would have occurred an average of about 17 times in 100 years. In comparison, the probability of obtaining the level actually measured in 1975 (after logging) was only about 0.017 if the area had not been logged. Such a level would only occur an average of 1.7 times in 100 years without timber removal. Thus, the occurrence of maximum levels was increased up to 10 times by timber removal.

CONCLUSIONS

Snowmelt is the primary climatic factor influencing piezometric levels in steep mountain areas in Idaho. Peak levels are not sensitive to instantaneous or mean daily snowmelt rates because of the influence of storage effects. Average ablation rates from the time of peak snow accumulation to the time of disappearance of the snowpack proved to be a good predictor of maximum and average piezometric levels on the study watersheds.

Timber removal influenced piezometric responses during snowmelt by increasing total snow accumulation, changing snow distribution, and increasing snow ablation rates. Logging caused most of the change in snow accumulation and melt. There was some suggestion of burning effects as well, but these were minimal compared with the logging effects. Using the relationship between mean ablation rates and peak piezometric levels coupled with the known changes in ablation rates caused by the logging, it was possible to predict the effects of logging on peak piezometric levels. On the average, logging increased maximum levels by 41 percent and average levels by 68 percent. A probability analysis of annual maximum levels suggests that their frequency was increased up to 10 times by timber removal.

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Long-Term Groundwater Monitoring in Mountainous Terrain

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ABSTRACT

Groundwater peak flows that trigger landslides in the northern Rocky Mountains occur in the winter and early spring when access is limited. The Forest Service, U.S. Department of Agriculture, is developing instrumentation for monitoring groundwater under these conditions. The system operates unattended under extreme weather conditions for 9 months, powered by rechargeable batteries; stores groundwater data on solid-state integrated-circuit storage modules that can be read directly into a host computer for data processing; is adaptable to precipitation monitoring; and is relatively inexpensive. Instrumentation and installation problems, as well as remedial measures, are discussed. Sample field data recovered since 1981 and practical applications of that data, including groundwater rise in response to precipitation modeling, landslide correction, and aquifer analysis, are discussed.

Groundwater in mountainous forest lands is the most dynamic variable to deal with in a slope stability analysis because it fluctuates constantly in response to precipitation. In spite of this, little groundwater monitoring has been done and few response models have been developed for watershed analysis. Likewise, geotechnical engineers, who may go to great lengths to determine more exact values for the other variables in a stability analysis, will often assume a value for the critical phreatic surface that is not based on groundwater-monitoring data. One basic reason for insufficient monitoring to support predictions is that dependable, inexpensive, long-term monitoring instrumentation currently is not commercially available. This paper is a progress report on a feasibility study to develop this methodology.

PHYSIOGRAPHIC SETTING

Groundwater concentration and flow in forest watersheds in the northern Rockies is dictated largely by physiographic conditions. Precipitation at higher elevations is mostly in the form of snow that can yield equivalent annual rainfall of 50 to 100 in. or more, although the neighboring valleys may receive less than 20 in. The manner in which this snow melts in the spring is a key factor in the determination of the seasonally high groundwater level. At the upper reaches of the watersheds, organic matter and windblown material such as volcanic ash are abundant near the ground surface. As a result, most of the snowmelt enters the ground with little overland sur-