CHANGES IN SOIL MOISTURE AND PORE PRESSURE AFTER HARVESTING A FORESTED HILLSLOPE IN NORTHERN CALIFORNIA

Elizabeth T. Keppeler[1], Robert R. Ziemer[1], and Peter H. Cafferata[2]

ABSTRACT: In 1987, a 0.83-ha zero-order swale was instrumented with 58 pierometers and 25 tensiometers along several hillslope transects. Through 1993, soil moisture conditions were measured by pressure transducers connected to a digital data logger recording at 15-minute intervals. In August 1989, the 100-year-old second-growth forest in the swale was felled. Logs were removed by cable yarding and heavy logging equipment was excluded from the hillslopes. Increases in peak piezometric levels and soil moisture were observed following logging. In the shallower, unsaturated portion of the soil profile, the increase was short-lived due to the rapid resprouting of redwood stumps. At the soil-bedrock interface, increased pore pressures persisted during winter periods throughout the 4-yr post-harvest period. In addition to changes in evapotranspiration, pore pressure increases may be explained by reduced canopy interception, compaction, or the collapse of soil pipes. At the base of the swale, pipeflow accounted for virtually all of the stormflow. After logging, soil pipes continued to efficiently route surplus stormflows through an existing piping network and no slope instabilities were observed.
KEY TERMS: hillslope hydrology, piezometer, soil moisture, timber harvest, soil piping.

INTRODUCTION

The impacts of timber harvesting on hydrologic processes are of great concern to land managers and the public in the Pacific Northwest. Many scientists have evaluated the effects of logging on streamflow and sedimentation but much less work has been done on subsurface flow processes. Slope stability problems arise on steep slopes where subsurface drainage is inefficient. The resultant mass erosion events are the major source of sedimentation in this region. It is now known that logging roads can alter subsurface flow conditions and aggravate slope stability hazards (Megahan, 1972). It is not clear if timber felling and skyline yarding alone can significantly affect the physical properties that govern hillslope drainage processes. This study addresses this issue by comparing pre- and post-harvest pore pressure levels and soil moisture conditions on a steep hillslope within a zero-order basin in coastal northwestern California.

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[1]Hydrologist and Chief Research Hydrologist, USDA Forest Service, PSW Research Station, 1700 Bayview Dr., Arcata, CA, 95521.

[2]Forest Hydrologist, California Dept. of Forestry and Fire Protection, 1416 9th St., Sacramento, CA, 95814.

Subsurface flow accounts for nearly all the water that is delivered to the stream channel system on undisturbed, steep, forested hillslopes (Harr, 1977). Precipitation infiltrating the soil surface travels through the soil matrix either as shallow subsurface stormflow or deep seepage to replenish groundwater storage. In many locations, large interconnected structural voids form soil pipes capable of intercepting and transporting subsurface discharge quite efficiently (Kirkby, 1978). In such cases, the hydraulic conductivity of the soil matrix is of secondary importance in generating stormflow (Whipkey, 1965; Mosley, 1979).

Timber harvesting operations affect hydrologic processes by reducing canopy interception and evapotranspiration. Many studies have documented changes in soil properties following tractor yarding (Stone, 1977; Cafferata, 1983), and low-ground-pressure skidding (Sidle and Drlica, 1981). More recently, researchers have evaluated cable yarding (Miller and Sirois, 1986; Purser and Cundy, 1992). In general, these studies report decreased hydraulic conductivity and increased bulk density in forest soils after harvest. Research on the effects of timber harvest on slope stability has produced varying conclusions (Ziemer, 198 1).

METHODS

Study Area

The study site is within the headwaters of the North Fork of Caspar Creek Experimental Watershed, on the Jackson Demonstration State Forest, Mendocino County, California. Caspar Creek is a 2145-ha coastal basin extending 10 km inland from the Pacific Ocean. The 483-ha North Fork drainage has been gauged continuously since 1962 as part of a comprehensive study evaluating the effects of logging on streamflow and water quality.

The study swales, M and K, are moderately steep zero-order basins located in the headwaters of the North Fork at an elevation of about 300 m. Their respective drainage areas are 1.69 and 0.83 ha (Figure 1). The topography is youthful, consisting of uplifted marine terraces that date to the late Tertiary and Quaternary periods. Slopes are moderate, ranging from 30 percent near ridges to 70 percent near stream channels.

The soils are formed from highly fractured sedimentary rocks, primarily Franciscan graywacke sandstone. The dominant soil series at the study site is Van Damme, a clayey, mixed isomesic typic tropudult. It is generally well-drained. but has highly variable permeability due to the occurrence of colluvial material. Saturated conductivity for this soil averages 2.4×10^{-2} cm sec^{-1} (87 cm hr^{-1}) in the upper 2 m, and decreases with depth (Wosika, 1981). Soil textures are loams at the surface and clay loams, with 35 to 45 percent clay, in the subsoil.

The climate of the Caspar Creek area is characteristic of the rain-dominated region of the Pacific Northwest. Summers are dry and mild, while winters are moderately wet. Snowfall is rare and hydrologically insignificant. Annual precipitation averages 1190 mm and falls for the most part between the months of October and April. Temperatures range from a summer maximum of about 25 degrees C to near freezing at the winter minimum.

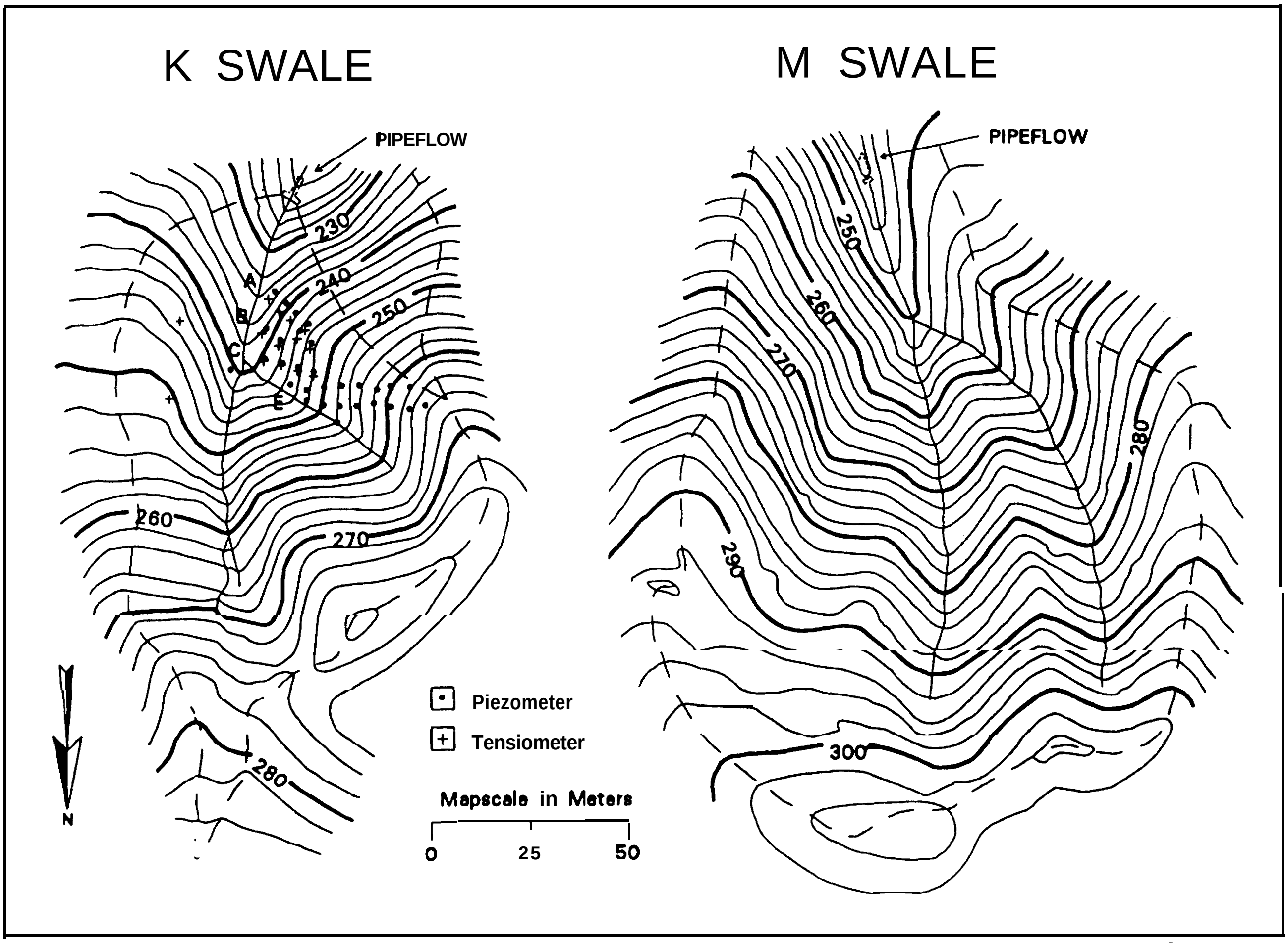

Figure 1. Caspar Creek Subsurface Study Swales: K Swale (Logged) and M Swale (Control).

The vegetative community is a redwood/Douglas-fir forest type. Nearly all the old-growth trees were removed prior to 1900. Second-growth tree species found in the basin include coastal redwood (Sequoia sempervirens (D.Don) Endl.), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), grand fir (Abies grandis (Dougl. ex D.Don) Lindl.), western hemlock Tsuga heterophvlla (Raf.) Sarg.), tanoak (Lithocarpus densiflorus (Hook. and Arn.) Rohn) and Pacific madrone (Arbutus menziesii Pursh.)

instrumentation

Two swales were instrumented for this analysis. The M swale served as an untreated control, while the K swale was logged. Soil pipe discharge was monitored at both swales. Subsurface pressure heads and soil moisture tensions were monitored in the K swale. Precipitation was measured by a recording tipping bucket rainguage.

The pipeflow installations were developed in 1986. Pipe outflows, occurring between 0.5 and 2 m below the ground surface, were exposed by trenching or enlarging existing collapse features (Albright, 1992). At the exposed vertical soil face, emerging pipeflow was captured by metal flashing and routed through plastic pipe to a calibrated discharge container with drain holes or slots. The water level in this calibrated discharge container was recorded at I0-minute intervals by a pressure transducer and an electronic data logger.

During summer 1987, a network of piezometers was established along five hillslope transects aligned perpendicular to the southwest facing slope in the K swale. A total of 58 piezometers were installed by hand auger, 31 to the bedrock surface and the other 27 to a depth of 1.5 m, approximating the subsoil/weathered bedrock interface. The depths of the bedrock piezometers ranged from 1.8 to 8 m. Instruments were located at 5 m intervals (slope distance) along each transect. The piezometers were constructed of 4 cm (I.D.) PVC pipe with the lower 15 cm of each pipe slotted and covered with a fine mesh screen.

The piezometers were initially monitored using a hand-held water level detector. In 1988 the more responsive piezometers were instrumented with electronic pressure transducers and connected to a 26-channel data logger. The transducers were interrogated at 15-minute intervals. All piezometers were manually checked at least once per week and more frequently during and following rainy periods.

In addition to the piezometers, 25 soil tensiometers were installed along transects A, B, and C to provide a measure of soil moisture during unsaturated conditions. These were installed at depths of 30, 45, 60, 120, and 150 cm. Transect C tensiometers were monitored with electronic pressure transducers connected to the aforementioned data logger. Vacuum dial gauges on the remaining tensiometers were read at least weekly. Tensions ranging up to 85 cb could be obtained with this equipment.

Timber Harvest Treatment

Following two winters of data collection, the K swale was clearcut and skyline yarded during August 1989, as part of a 16-ha commercial timber sale unit. Ground skidding equipment was restricted to the ridges for constructing a spur road and landing. No slash burning or other site preparation was done following the timber harvest. The following spring, the unit was interplanted with redwood seedlings, excluding areas next to redwood stump sprouts.

Immediately prior to the logging, the piezometers were cut and capped about 40 cm below the ground surface. The tensiometers were removed and replaced with dowel. Upon completion of the timber harvest in September 1989, the instruments were reinstalled and data collection resumed through hydrologic year 1993.

Data Analysis

Positive pore pressure responses were detected in 19 of the 31 bedrock surface sites. Six piezometers (the lower three instruments on the C and E transects) were chosen for immediate evaluation. These six represent a range of hillslope positions where reliable electronic data was collected. The data were analyzed for changes in the magnitudes of the peak pressure response and inter-storm minimums, timing of the storm peak response, and seasonal minimums. All statistical tests were performed at the 0.05 probability level unless otherwise stated.

Storm peaks selected for analysis were restricted to those where the piezograph showed a minimum rise of 5 cm in response to a discrete storm event accompanied by a corresponding rise in the unlogged control pipe M106 discharge. The storm events meeting these criteria generally excluded those totalling less than 5 cm of precipitation. This selection process yielded 12 pre-logging and 61 post-logging events in the five-year data set.

Least-squares regression was used to develop calibration and post--treatment relationships between pipe discharge at the M control swale and the water surface elevations in the K swale piezometers. To normalize error terms, the $\log_{10}$ of pipe discharge was used as the independent variable. Separate regressions were calculated for the pre-logging data and the post-logging data. In addition, separate regressions were done for hydrologic years 1990 and 1993 to determine if changes were detectable in the first year following logging and to determine if recovery had begun by 1993. Zar's test for comparing regression parameters was then applied (Zar, 1974). The predicted change in piezometric peak was calculated at the mean pipeflow discharge of 119 l min^{-1} using the pre- and post-logging regressions. A similar procedure was applied to detect post-logging changes in minimum piezometric water surfaces during winter inter-storm periods.

To examine changes in lag time, the timing of peak pipe discharge and peak piezometric water surfaces were compared for the same set of storms described above. The difference between piping peak time and piezometer peak time was calculated. A simple t-test was used to compare the mean time difference before and after harvest.

In the spring, saturated conditions on the study hillslope diminish. To detect late season changes in hillslope saturation following logging, control pipe M106 discharge levels were compared across years on the date when the transect E piezometers ceased to indicate saturation. In addition, tensiometer data were compared across years to determine if soil moisture conditions in the upper 150 cm of the soil profile were affected by logging.

Lastly, to determine if the annual minimum piezometric water surface was altered by logging, water surface elevations for those sites with year-round saturation were compared across years on September 30th, a date when piezometric levels were found to be at a stable minimum.

RESULTS

Analysis of pore pressure responses for the six selected piezometers regressed on pipe discharge at the M control swale indicates post-logging peaks were greater than pre-logging peaks. In all cases the post-logging regression equations were significantly different than the pre-logging equations. The post-logging intercept term was greater in all cases ($p = 0.005$). For four of the six piezometers analyzed, the slope term of the post-logging regression was significantly less than the pre-logging estimate (Table 1). In addition, the individual 1990 and 1993 post-logging regressions were significantly different than the pre-logging regression.

Time-to-peak comparisons between pipeflow at the control site and pressure heads at the treated swale did not detect a logging effect due to the large variance in peak timing.

Table 1. Comparison of Storm Peak Regression Analysis Results: K Piezometric Peaks Regressed on Pipe Discharge at the M control site.

SITE	PRE-LOGGING			POST-LOGGING		
	r^2adj	a	b	r^2adj	a	b
CIP2	0.78	237.96	0.2037	0.76	238.07*	0.1812*
C2P2	0.85	239.61	0.3916	0.79	239.99*	0.2530*
C3P2	0.94	241.84	0.3352	0.85	242.20*	0.2757*
EIP2	0.98	245.11	0.4581	0.81	245.52*	0.4327
E2P2	0.95	246.13	0.6459	0.77	246.59*	0.6125
E3P2	0.98	246.63	1.0927	0.76	247.91*	0.7736*

r^2adj = coefficient of determination adjusted for degrees of freedom
a = intercept estimate of regression equation
b = slope estimate of regression equation
* significantly different from pre-logging estimate ($p = 0.05$)

Analysis of inter-storm lows, or troughs, suggests a response similar to that of the storm peaks. The post-logging regression parameters were significantly different than the calibration estimates for the three piezometers evaluated. Again, the intercept terms were most changed (Table 2).

Table 2. Comparison of Regression Analysis Results for Inter-Storm Lows: K Piezometric Levels Regressed on Pipe Discharge at the M Control Site.

SITE	PRE-LOGGING			POST-LOGGING		
	r^2adj	a	b	r^2adj	a	b
CIP2	0.62	237.98	0.1287	0.65	238.10*	0.0972*
C3P2	0.92	242.04	0.1641	0.74	242.22*	0.1828*
El P2	0.83	245.24	0.2634	0.72	245.46*	0.6058*

r^2adj = coefficient of determination adjusted for degrees of freedom
a = intercept estimate of regression equation
b = slope estimate of regression equation
* significantly different from pre-logging estimate ($p = 0.05$)

A comparison of pipeflow at the unlogged swale to piezometer levels along the E transect suggests saturated conditions persisted longer into the early summer following logging. However, no difference could be detected at the end of the dry season.

Examination of the tensiometer data reveals that prior to logging, tensions for all depths in the soil profile remained near saturation into the spring, and then slowly rose to the point of cavitation by August. Approximately 10 cm of precipitation were required to saturate the profile for the shallower tensiometers, while about 25 cm were needed at depths exceeding 1 m. Throughout the first summer season following logging, the soil profile remained significantly more moist at depths of 120 and 150 cm. By the second year, however, soil moisture tensions at these depths climbed more rapidly. By hydrologic year 1993, the tensions reached by most of the instruments approximated those recorded prior to harvest (Figure 2). Exceptions to this general trend exist, perhaps due to the relative location of tree roots and the tensiometers. The short duration of this response may be explained by rapid resprouting of the redwood stumps and reuse of the parent tree's extensive root network (Ziemer, 1981).

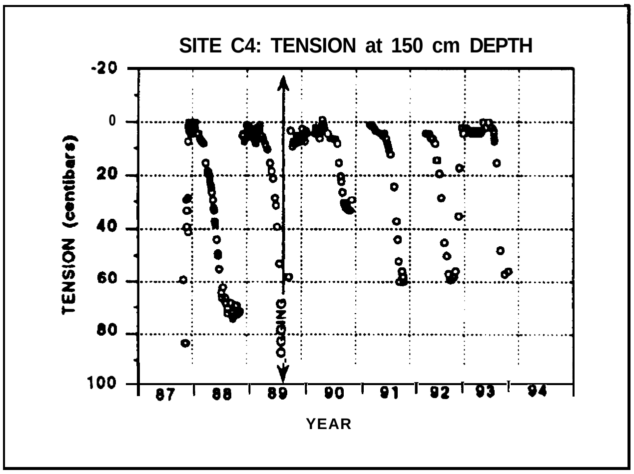

Figure 2. Soil Moisture Tensions at K Swale.

DISCUSSION

Research in the headwaters of the Caspar Creek watershed has revealed several details about subsurface drainage processes following timber harvest. Both before and after harvest, elevated pore water pressures occurred above competent bedrock during rainy periods, particularly at positions low on the hillslope. In other locations, the lack of saturated response demonstrates the high permeability of the weathered sandstone bedrock.

Storm piezometric response showed that post-logging water surface levels were higher than pre-logging. Although the response patterns of neighboring piezometers were not uniform, the range in piezometric levels for lower hillslope positions was substantially smaller than that of upslope piezometers (Figure 3). Because of higher soil moisture content and the presence of preferential pathways in the saturated wedge, pore pressure responses tend to be less variable at the base of a hillslope (Sidle and Tsuboyama, 1992). Furthermore, the greatest range in peak response and the

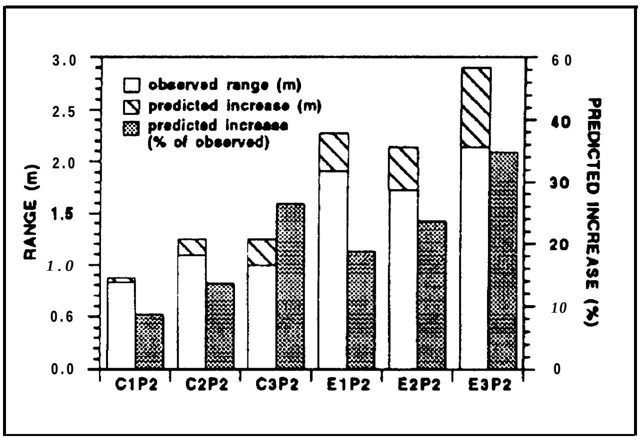

Figure 3. Range in Peak Piezometric Levels and Predicted Post-logging Increases.

largest increases were observed in the upslope (E transect) piezometers. At the mean peak pipe discharge of 119 l min^{-1}, predicted peak piezometric levels were 9 to 35% above pre-logging levels (Figure 3). Megahan (1983, 1984) reported increased peak piezometric rises of 47% following clearcutting and wildfire on steep granitic slopes in Idaho. Much of the increase in Idaho was attributed to increased snow accumulation and melt rates. In contrast, our results suggest evapotranspiration plays a more significant hydrologic role on slopes in this milder, rain-dominated climate. Low-level winter evapotranspiration is common in redwood-Douglas-fir forests, When storms are infrequent, it is likely that the forested swale had considerably drier soil at the start of a rainfall event. Except for 1993, the weather pattern for northern California during this 5-yr period was abnormally dry and large storms were rare. Thus, conditions favored the development of inter-storm soil moisture deficits in the forested control swale.

Differences due to evapotranspiration alone are insufficient to explain the observed increases in piezometric levels. Of the six piezometers analyzed, four regression lines exhibited a decreased slope in the post-logging period (Figure 4). This suggests that post-logging responses would not be dramatically increased for larger storms occurring during fully saturated conditions. The largest storm occurred in January 1993 during a period of frequent rainfall and had an estimated return period of nine years. With the exception of C2P2, the peak response to this storm was greater than predicted by the calibration regression. Differences in soil moisture storage between the control and logged sites were negligible during this rainy period, suggesting additional hydrologic changes. In addition to

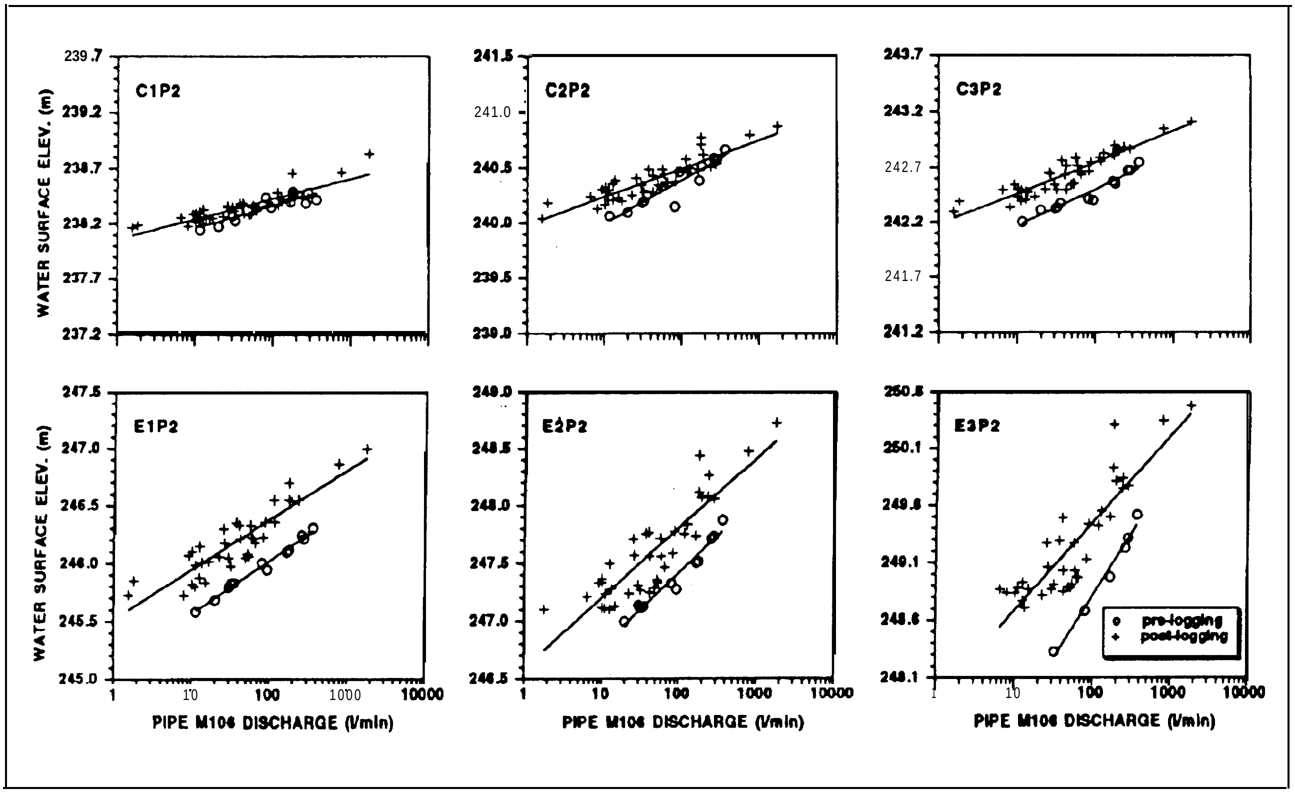

Figure 4. Peak Water Surface Elevations Before and After Timber Harvest in the K Swale versus Peak Pipeflow in the Unlogged M Control Swale.

altered evapotranspiration, observed increases in pore water pressure may be explained by reduced canopy interception, compaction induced reductions in pore space, or the collapse of soil pipes due to felling and yarding. Although Ziemer (1992) reported a nearly four fold increase in peak soil pipe discharge at the base of the K swale following logging, matrix flow does not appear to have been comparably enhanced. It is probable that following logging the piping network efficiently captured and routed soil matrix flow as excess pore water pressures developed and thus prevented associated large rises in piezometric levels. Further field work is needed to document flow paths and to quantitatively estimate subsurface discharge rates.

Enhancement of saturated subsurface flows persisted well into the drier spring season following logging. However, these data provide only a glimpse of groundwater conditions during the baseflow season at Caspar Creek. During the drier spring and summer months, most of the piezometers are dry. The few that do maintain year-round positive levels are located near the base of the slope. Although summer pipe discharge at the K piping site increased after logging, it is not surprising that no change was detected in minimum piezometric levels at these permanently saturated locations. Subsurface discharges may have dropped to a point where the change in pressure head was not discernable with the existing instrumentation.

CONCLUSION

Clearcut logging and skyline yarding can affect subsurface hydrologic processes in the redwood/Douglas-fir region,. This study demonstrates that pore water pressures increased following logging for the 4-yr post-harvest period. Soil moisture in the upper soil profile was also enhanced although the resprouting redwood forest quickly utilized most of the excess soil water in the phreatic zone. The implications of these increases to slope stability are more difficult to ascertain. No slope failures were observed in the logged swale, nor was evidence of potential landsliding detected. Increased piezometric responses could not be translated into quantitative subsurface discharge rates using available data. It is, however, plausible that on slopes with known or suspected stability problems, the additional pore water pressure generated by timber removal could increase the risk of landsliding.

This study, along with previous and ongoing Caspar Creek research, provides further evidence that a major subsurface storm flow component is captured and efficiently routed through an existing piping network. Serious slope stability problems may arise if soil pipes are collapsed by logging operations or other disturbance. For this reason, land mangers are cautioned to carefully evaluate the use of heavy equipment on forested slopes where soil piping is believed to occur.

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