Subsurface Drainage Processes and Management Impacts[1]

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Abstract: *Storm-induced streamflow in forested upland watersheds is linked to rainfall by transient, variably saturated flow through several different flow paths. In the absence of exposed bedrock, shallow flow-restrictive layers, or compacted soil surfaces, virtually all of the infiltrated rainfall reaches the stream as subsurface flow. Subsurface runoff can occur within micropores (voids between soil grains), various types of macropores (structural voids between aggregates, plant and animal-induced biopores), and through fractures in weathered and consolidated bedrock. In addition to generating flow through the subsurface, transient rain events can also cause large increases in fluid pressures within a hillslope. If pore pressures exceed stability limits of soils and shallow geologic materials, landslides and debris flows may result. Subsurface monitoring of pipeflows and pore pressures in unchanneled swales at North Fork Caspar Creek in the Jackson Demonstration State Forest began in 1985. Four sites have been established to investigate the effects of timber harvest (K1 and K2) and road building (E-road) for comparison with an unmanaged control drainage (M1). Flow through large soil pipes at these sites is highly transient in response to storm events, reaching peak discharges on the order of 100 to 1,000 L min^{-1}. Pore pressures at these sites also respond dynamically to transient rain events, but to date have not exceeded slope stability limits. Most soil pipes cease flowing in the dry summer period and hillslope soil moisture declines to far below saturation. The clearcut logging and skyline-cable yarding of the K2 site resulted in dramatic increases in soil pipeflow and subsurface pore pressures. During the first 4 years after timber harvest, pore pressures increased 9 to 35 percent for the mean peak storm event in the control M1 site. Peak soil pipeflow response was far greater, increasing 400 percent in the 4-year postlogging period. These results suggest that the soil pipes are a critical component of subsurface hillslope drainage, acting to moderate the pore pressure response. As the subsoil matrix becomes saturated and pore pressures build, soil pipes efficiently capture excess water and route it to the stream channel. This logging does not appear to have impaired the hillslope drainage function. Methods and results at the E-road site are quite different. Here, the mid-swale road construction and tractor yarding have resulted in large changes in the pore pressure response. Positive pore pressures were negligible in the upper portion of this instrumented swale before disturbance. Subsequent to the road construction in May 1990, there was little indication of immediate impacts. But, after the completion of felling and tractor yarding in late summer 1991, dramatic changes in pore pressure response were observed beginning in hydrologic year 1993 and continuing to date (1998). Largest pore pressure increases have occurred at sensor locations in and up-slope of the road prism. Below the road, the response is muted. These data support previous studies documenting the profound effects of roading and tractor logging on watersheds and provide special insight into these effects for this region.*

The hydrologic response of forested watersheds to rain events occurs through several interrelated flow processes. Soil surface conditions determine whether rainfall will run off as surface flow or whether it will infiltrate and travel through the subsurface. Infiltration capacities for soils in the coastal redwood region exceed maximum rainfall intensities common in the region. Exceptions occur in isolated areas where bedrock is exposed at the land surface. More widespread are infiltration limitations resulting from soil compaction associated with road building, landings, and other constructed surfaces. Over the great majority of forested landscapes, rainfall infiltrates into the soil and flows through the subsurface to streams, rivers, and lakes.

Subsurface flow may occur within soil horizons, regolith (weathered bedrock), or bedrock (*fig. 1*). The conductive and storage properties of a given earth material as well as the spatial relations of adjoining materials strongly influence the actual flow path through the subsurface. For example, water may flow within soil horizons through the matrix, a porous medium of individual grains. Pores on the individual grain scale transmit water very slowly, several orders of magnitude less than surface water flows. Larger pores (on the order of 1 mm in diameter or larger) are commonly referred to as macropores, and can conduct substantial quantities of water at rates approaching surface flow velocities. By virtue of their geometry, macropores can be shown to conduct water more rapidly under high moisture conditions than the "micropores" of the soil matrix. Macropore geometry and type varies with depth below the land surface arising from various biologic and soil-forming processes (*fig. 1*). Interconnected large macropores (on the order of 2 cm in diameter or larger) are often referred to as "soil pipes." These features are erosion pathways that extend within the shallow subsurface horizons as continuous or interconnected conduits forming complex branching networks (Albright 1992). An important hydrologic attribute of macropores is that the surrounding soils must be saturated before water can flow into these large pores. Thus, the antecedent moisture conditions in forest soils strongly control the importance of flow through macropores; and hence, the hydrologic response of a watershed to a precipitation event. Similarly, fractures in regolith or bedrock may dominate the flow response under saturated conditions, and thus define a significant flow path distinct from the soil matrix or macropores.

The movement of water into and through these flow paths has two consequences of both theoretical interest and practical application to the management of forestlands. First, surface runoff in streams is generated on two widely different time scales: (1) on a seasonal basis and (2) during individual precipitation events. Runoff volume, timing, and duration affect both water supply and flood propagation. Seasonal effects of subsurface flows are manifest in the storage properties of forest soils. During the summer, water

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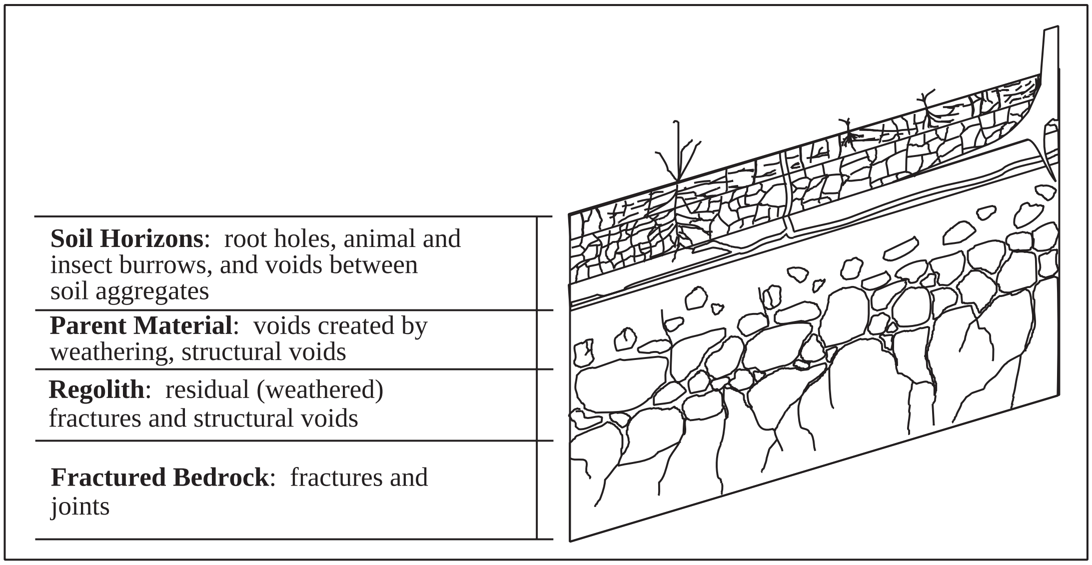


Figure 1—Hypothetical soil cross-section with characteristic voids and flow path variations.

drains from soils and supports perennial streamflow (baseflow). This drainage creates a water deficit in the soil that must be replenished before maximum flow through a hillslope can occur.

The second consequence of transient subsurface flow is directly related to the storm-driven evolution of pore pressures at the hillslope scale. Gravity is the primary force driving the flow of water in upland forested watersheds. However, if soil compaction closes pore spaces and prevents or reduces drainage through macropores, water pressure may increase such that the strength of the hillslope is lost and shallow landslides or debris flows may occur. Mass failures are a significant source of sediment reaching streams and are generated from background earth surface processes and from human activities such as road building. Dynamic interactions between pore pressures, drainage geometry, and the material properties of soil and bedrock can significantly influence the stability of slopes and channel heads, as well as sediment releases to streams (Dietrich and others 1986).

Research investigations at Caspar Creek have explored these hillslope and subsurface drainage processes with the dual objectives of identifying impacts associated with logging and road building and reducing the risk of mass failures associated with timber harvest activities in the redwood region.

Methods

Headwater swales were selected for monitoring in both a control (MUN) and two designated treatment sub-basins (KJE and EAG) of the North Fork experimental watershed (Preface, fig. 2, these proceedings). All study sites are moderately steep zero-order basins located in the North Fork watershed at an approximate elevation of 300 m (*fig. 2*). An almost 100-year-old second-growth forest occupied these sites at the initiation of these investigations (Henry, these proceedings). All study swales are drained by one or more soil pipes with outflow in evidence at the base of the swale axis. Pipeflow varies seasonally from less than 0.01 L min^{-1} to more than 1,000 L min^{-1} at individual soil pipes. Most soil pipes are intermittent or seasonally dry.

The vegetation community is a coniferous forest type with a

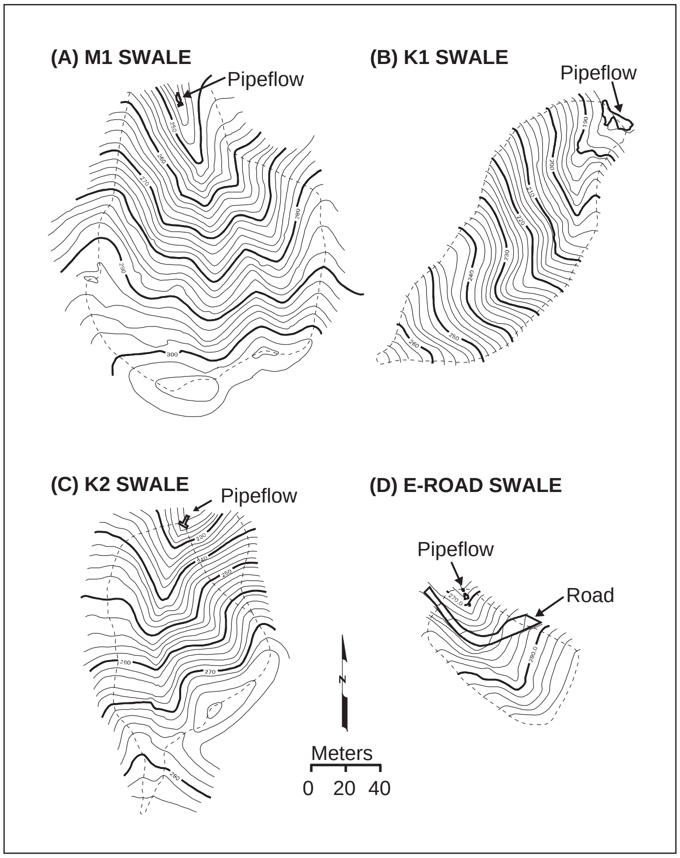


Figure 2—North Fork Caspar Creek study swales (2-m contour interval).

closed canopy consisting of coastal redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) as the dominant tree species. Although not measured during this study, the diameter-at-breast height is estimated to range from approximately 0.3 m to 1.5 m. Forests in the Caspar Creek watersheds were clearcut and burned in the late 1800's (Tilley and Rice 1977; Napolitano, these proceedings), and are generally typical second-growth forests. Other tree species occurring at this site include grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and tanoak (*Lithocarpus densiflorus* (Hook. and Arn.) Rohn).

The soil at these sites has been classified as a clayey, mixed isomesic Typic Tropudult described as the Van Damme series (Huff and others 1985). Surface soils tend to have a loamy texture and increasing clay content with depth (Wosika 1981). Discontinuous argillic horizons have been observed in scattered soil pits (Dahlgren 1998). Soil thicknesses range from 1.0 m along the ridges to 1.5 m in the swales (Wosika 1981). The parent material below this depth range is a highly weathered layer of fractured regolith derived from the underlying graywacke sandstone of Cretaceous age known as the Franciscan Assemblage (Huff and others 1985). Geologically recent tectonic forces (1 my b.p.) acting along the San Andreas fault system just offshore have contributed to a gradual uplift of up to 200 m (Jenny 1980). Field estimates of hydraulic conductivities were made using slug tests in piezometers in EAG, KJE, and MUN swales. Saturated hydraulic conductivity estimates for the regolith above the hard bedrock contact range on the order of 10^{-8} to 10^{-4} m s^{-1}.

Local climate is heavily influenced by the site's proximity to the coast (approximately 10 km to the west). Like most of coastal California, the large majority of the rainfall occurs during late fall and winter months. The mean annual rainfall for this area is 1190 mm (46.85 in). Relatively little rainfall occurs between the months of April and October, but coastal fog may supply moisture to the soils via fog drip. Air temperatures range from a January mean of 7 °C to a high of about 15 °C in July.

M1 Site

The M1 site is the designated control site and thus retains continuous second-growth forest cover. This 1.7-ha swale (*fig. 2a*) is the largest subsurface study site. The terrain slope varies from 20 to 50 percent. One large and several small soil pipes drain the swale. These soil pipes were fitted for instrumentation in 1986 (Ziemer and Albright 1987). The large 80 cm (height) by 60 cm (width) pipe, M106, has discharged the highest pipeflow peak recorded in the North Fork watershed—1,700 L min^{-1} on January 20, 1993. This pipe occurs at the interface between the upper soil and an argillic horizon (Albright 1992). Two transects of piezometers, denoted A (three instruments) and C (four instruments), were installed to bedrock (at depths of up to approximately 6.0 m) on the side slopes above the piping gage station (Brown 1995). A nest of piezometers was installed at the confluence of the two subswales. Two piezometer nests were installed at the confluence of the subswales (piezometers B1 and B2) and just upslope of the swale at the bottom of the C transect (piezometers C1 and C2). Two additional piezometers were installed to bedrock, one in each of the two upper tributary swales (Brown 1995). On the basis of the soil borings excavated during piezometer installations, a geologic cross-section was prepared across the A-C transects (*fig. 3*). Soil horizons and regolith thicknesses were fairly uniform throughout both slopes.

K1 Site

A second pipeflow site, K1, was developed near the KJE stream gaging station in 1986 (Preface, fig. 2, these proceedings). This 1.0-ha swale (*fig. 2b*) is drained by several soil pipes within the upper 0.5 m of the soil with diameters ranging from 10 to 20 cm (Albright 1992). Most are flashy and ephemeral, yielding significant flows only during storm events. Pipeflow, surface flow, and matrix flow at the soil face were gaged at this second site, but no subsurface pore pressure measurements were made. The site was clearcut and skyline yarded from the ridge in 1989 as part of the Caspar East timber sale unit K (Henry, these proceedings). No slash burning or other site preparation was done in this unit after timber harvest.

K2 Site

This 0.8-ha zero-order swale (*fig. 2c*) was first instrumented for pipeflow measurements in 1986. Three soil pipes were gaged at this site. The largest soil pipe, K201, is 50 cm in diameter and emerges from the exposed soil face at a depth of less than 1.5 m from the ground surface (Albright 1992). In 1987, a network of piezometers and tensiometers was established along five hillslope transects (Keppeler and others 1994) that were aligned perpendicular to a west-facing K2 hillslope. To prevent excessive disturbance of this steep 70 percent slope, a system of ladders and catwalks was built before instrument installation. Hillslope installations include: 31 bedrock piezometers, 27 1.5-m-deep piezometers, and 25 tensiometers at depths of 30, 45, 60, 120, and 150 cm. Three of these instrument transects (A, B, C) are about 20 m in length and extend from near the swale axis to mid-slope positions. The other

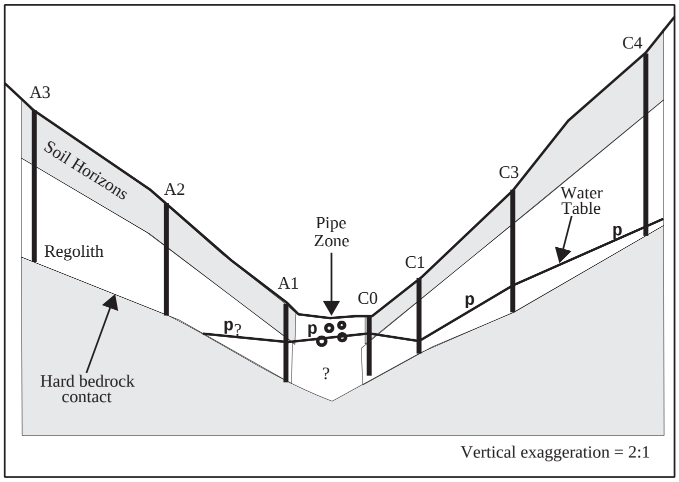


Figure 3—Cross-section of soils, geology, soil pipe, and piezometer installations at the M1 site.

two transects (D and E) extend nearly to the ridge. Two additional bedrock piezometers are installed in the swale axis. After two winters of data collection, the K2 site was clearcut and skyline yarded from the ridge during August 1989 (Henry, these proceedings). No slash burning or other site preparation was done in this unit following timber harvest.

E-Road Site

The smallest and most recent Caspar Creek subsurface monitoring site is the E-road swale. This 0.4-ha swale is located in the EAG subbasin and cutblock E of the North Fork (Preface, fig. 2, these proceedings). This north-facing swale is drained by two instrumented soil pipes. A single 44-m-long transect consisting of six bedrock and two shallower piezometer installations extends through the swale axis from the soil pipe excavation to a position 38 m from the ridge (*fig. 2d*). Piezometer depths range from < 1.5 m at the lower end of this transect to almost 8 m at the top. The terrain slope along this transect averages 35 percent. This site was instrumented in fall 1989 to evaluate the impacts of road construction on hillslope drainage processes. Predisturbance monitoring of pore pressures and pipeflow occurred during the winter 1990. In June 1990, a seasonal road was built across this swale to a yarder landing on the unit divide. The road centerline crosses the instrument transect at the R4P2 piezometer. The grade of this 30-m road segment averages 19 percent. The fill depth is 3 m at its maximum, 2 m at the centerline, 1.6 m at R3P2, and <1 m at R2P2 (near the base of the roadfill). This haul road was rocked for use during October and November of 1990 when a portion of the Unit E cutblock was harvested using a cable skyline yarder at the end of this spur. In late-summer 1991, the timber not cut during the road right-of-way felling was harvested using tractor yarding above and long-lining below the road. Broadcast burning of the unit occurred in late November. Because of the north-facing aspect of this swale, fuel consumption was incomplete.

Instrumentation

Field investigations were undertaken first to identify the most upslope occurrence of gullying or sinkholes associated with pipeflow outlets at each study swale. At these existing collapses, handcrews excavated a near-vertical soil face to facilitate the capture of pipeflow and soil matrix discharge. Soil pipes ranging in diameter from 2 to 60 cm and occurring within 2 m of the soil profile were instrumented. Flow from individual sources (pipes, overland flow, and soil matrix flow) was captured by first driving metal flashing collectors into the excavated soil profile, then connecting these collectors to PVC (polyvinyl chloride) pipe, and finally routing the flow into an upright PVC standpipe container. Drainage holes were drilled into these standpipe containers and a laboratory calibration was done to establish the relationship between stage in the container and discharge. Containers were designed with a variety of drain hole diameters and placements to accommodate a wide range of discharges. Using electronic pressure transducers and data loggers, container stages were recorded at 10-min intervals during the winter season and at 30-min intervals during the lowflow season. Frequent manual discharge measurements were made at these pipeflow sites to verify and refine the standpipe container calibrations (Ziemer and Albright 1987).

To measure the pore pressure response along selected transects in these study swales, piezometer wells were installed by hand-augering 10-cm-diameter holes through the soil profile. A PVC pipe (38 or 51 mm diameter) was then cut to extend from the base of the hole to several centimeters above the ground surface. The lower 15-cm length of this pipe was slotted with a hack saw. Plastic mesh screen was wrapped around the slotted portion of the pipe before the pipe was placed in the augered hole. The hole was backfilled first with pea gravel for about 25 cm of the depth, then 15 to 20 cm of bentonite, and finally, with natural soil. Hillslope instruments were assigned a transect identifier and numbered beginning with the base of the slope and progressing up the hill. P2 indicates a "bedrock" piezometer, and P1 indicates a shallower installation.

Bedrock installations were augered to the physical limit of the hand auger device. At some sites, rock fragments in the lower saprolite prevented the auger from reaching competent bedrock. Shallower piezometers were installed at certain sites where a low-permeability clay layer (argillic horizon) was encountered. Finally, a few piezometers were installed into competent bedrock using a rock drill. Water levels (pore pressures) were monitored using a combination of techniques. Manual measurements were made at all piezometers at least weekly using an electronic water surface detector. Electronic pressure transducers connected to a data logger sensed piezometer water levels at 15-min intervals during the winter and less frequently during the lowflow periods at the K2 and E-road swales (Keppeler and Cafferata 1991, Keppeler and others 1994). Accuracy of these measurements was generally within a 0.05-m tolerance. At the M1 site, a comparable transducer/data-logger combination provided water level heights with a design accuracy of approximately 0.01 m along three transects (A, B, and C). Only very rarely did the electronic data differ from hand measurements by more than 0.02 m. Pressure heads in the piezometers were logged at 15-min intervals during storm periods, and at 2-hr intervals between storms.

Soil tensiometers were installed at some sites to provide a measure of soil moisture in unsaturated conditions and to indicate when the shallower soil horizons became seasonally saturated. These devices are commonly used for assessing agricultural irrigation needs. Our tensiometers consist of a porous ceramic cup connected to a closed tube and a vacuum gage. The cup is buried in the soil and the tube is filled with water. As the soil moisture tension equilibrates with the water tension in the tube, a vacuum is created and indicated on the gage. At field capacity, this tension is 33 cb. As the soil drains, tensions exceeding 85 cb may be recorded. These gages were read manually at weekly intervals and, in some cases, connected to a data logger via a pressure transducer allowing for frequent readings and recordings. Keppeler (these proceedings) reports summer soil moisture changes at these sites.

Analyses

Ziemer (1992) evaluated changes in peak pipeflow after the logging of the K1 and K2 swales using data from hydrologic year 1987 through 1991. Regression analysis was used to develop a relationship between individual soil pipes at the K1 and K2 sites and the M1 site control, as well as total pipe discharge per site. A second set of regressions was developed using the postlogging pipeflow peaks. Chow's test (Chow 1960) was used to detect differences between these regression lines ($p < 0.05$). For this report, additional peak pipeflow data through hydrologic year 1993 from the K201 and M106 sources were analyzed using this regression approach. This analysis included 38 prelogging and 41 postlogging storm peak pairs from K201 and M106.

Keppeler and others (1994) evaluated the piezometric response to logging in the K2 site. Regression analysis was used to define the prelogging relationship between peak pore pressures along selected K2 transects and peak discharge ($\log_{10}$) at the M106 soil pipe. Postlogging regressions were then developed for storm peaks occurring during hydrologic years 1990-1993. Zar's test for comparing regression lines (Zar 1974) was used to detect differences between the calibration and postlogging relationships ($p < 0.05$). A similar procedure was applied to evaluate piezometric pressure heads during nonstorm periods.

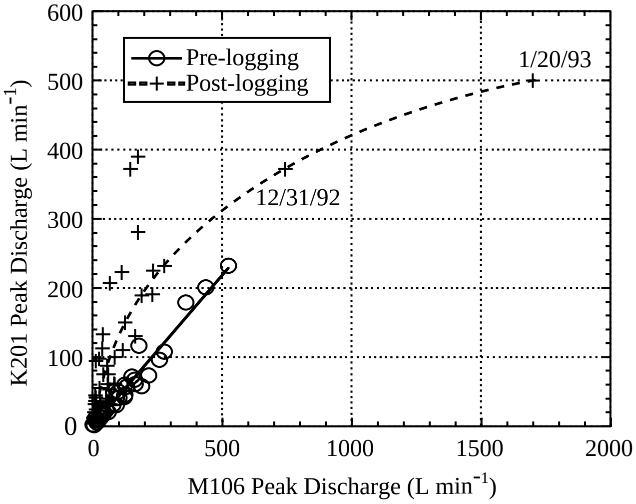
Initial analysis of the pore pressure response to road building was done nonstatistically by comparing E-road piezometric peaks and ranges before and after road construction and tractor logging. In addition, further analysis was attempted using E-road piezometer peaks regressed on peak discharge ($\log_{10}$) at the M106 soil pipe. Only preliminary screening of other factors relating to the E-road subsurface response has been performed.

Results and Discussion

Pipeflow

Increased peak pipeflow was detected at the fully clearcut K2 site during the first winter after logging (1990), but larger increases were observed one year later (Ziemer 1992). During 1990 and 1991, peak pipeflow at K2 (pipe K201) was 370 percent greater than predicted by the calibration relationship with M1 (pipe M106). Extending this analysis to include peak discharges through 1993 provides further insight into the pipeflow response to logging. With 38 peaks ranging up to 525 L min^{-1} (M106) in the prelogging data set, a linear regression provides a very good fit to the data ($r^2 = 0.96$) as evident in *figure 4b*. The postlogging data set contains 41 peaks, with all but two of the M106 peak discharges less than 300 L min^{-1}. Those two large peaks exceed the prelogging data by a substantial margin (*fig. 4a*), and present an interesting complication to evaluating treatment effects. The largest storm produced a peak at M106 of 1700 L min^{-1} on January 20, 1993, triple the size of the largest M106 peak in the prelogging data set. The return interval for this peak is approximately 8 years based on the 35-yr North Fork peakflow record. The postlogging relationship between M106 and K201 is much more variable than the prelogging relationship. Although pipe K201 yields maximum discharges of up to 500 L min^{-1}, it appears to be capable of unrestricted discharge only until about 250 L min^{-1}. The recurrence interval of the comparable North Fork streamflow peak is approximately 0.3 years. K201 discharge appears to be restricted by pipe capacity above a discharge of about 250 L min^{-1}, whereas M106 can pass discharges of at least 1,700 L min^{-1}. The other instrumented soil pipes also exhibit peak discharge restrictions at even lower discharges. In contrast to open channel conditions, pipeflow is limited by the physical capacity of the pipe. The cross-sectional area of pipe K201 is much less than M106; thus, discharge capacity at K201 is more limited than M106. Field observations indicate that upslope of the M1, K2, and K1 gaging sites; several ungaged pipe outlets produce significant discharge volumes during larger storm peaks. These "overflow" features provide further evidence of the hydraulic limitations of these main soil pipe pathways.

a) K201 (logged 1989) versus M106 (unlogged control)



b) M106 Discharge < 300 L min^{-1}

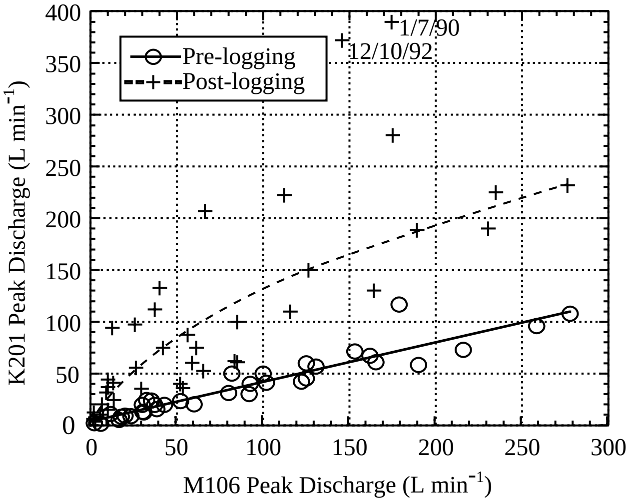


Figure 4—A comparison of the peak pipeflow response from M106 (unlogged control) and K201 (clearcut in 1989) and regression lines. The solid line is the linear fit to the prelogging data. The dashed line is the locally fitted regression of the postlogging data and is approximated by a second-order polynomial fit to a log-log relationship. Plot (a) includes all data. Plot (b) excludes the larger M106 peaks where K201 begins to exhibit capacity limitations.

Because of these physical limitations, a linear regression analysis of the postlogging K201 and M106 peakflow data is not appropriate for moderate to high peak discharges. However, it is clear that a substantial increase in K201 pipeflow occurred after logging *(fig. 4)*. When the postlogging data are fit by a locally weighted regression (Cleveland 1993), it is evident that the greatest departures from pretreatment data occur at discharges of less than 200 L min^{-1} at M106. Above this level, K201 peaks begin to level off. When the M106 discharges exceed 500 L min^{-1}, it is not possible to detect any postlogging change in K201 discharge peaks. The prelogging regression equation predicts that at the mean M106 peak pipeflow of 118 L min^{-1} the expected K201 peak is 51 L min^{-1}, but the postlogging locally weighted regression predicts a peak of 143 L min^{-1} — a 280 percent increase (*fig. 4b*).

The maximum postlogging increase at K201 was more than 300 L min^{-1} for two moderate storm events that occurred January 7, 1990 and December 10, 1992 (*fig. 4b*). These storms produced discharges at North Fork Caspar with return intervals of 1.7 times per year. The largest proportionate increases in pipe peakflow occurred during two minor storms in February 1991, when winter rainfall totals had been far below normal. These were the first stormflow responses at M1 for that year indicating that antecedent soil moisture conditions were just reaching saturation, whereas K2 soils were more fully saturated. As previously explained, the soil in the vicinity of the pipe pathway must be saturated before water can flow through these conduits. Ziemer's evaluation of Caspar Creek streamflow peaks (these proceedings) states that the largest increases in peak discharges occur when the greatest differences in soil moisture exist between the logged and forested watersheds.

At K1, peakflow from instrumented soil pipes did not show a significant increase (Ziemer 1992). However, an additional pipe outlet located about 30 m upslope of the pipeflow gaging instrumentation began to discharge storm flows. This source flowed rarely before logging, but regularly during storm events after logging, suggesting that the capacity of the K1 soil pipes was quite limited in comparison to either K201 or M106. When the discharge from this source is added to that of the other instrumented K1 pipes, the K1 peakflow increase approximates the increase observed at K201 (Ziemer 1992).

Keppeler (these proceedings) reports increases in minimum summer pipeflow, as well. The duration of these postlogging increases has yet to be documented.

M1 Pore Pressures

The water table throughout the entire monitoring period was observed only along the regolith-hard bedrock interface. A typical water table profile across the A-C transects during late February 1994 is shown in *figure 3*. On the basis of field observations of the soil pipes emerging at the pipeflow gages, it appears that the pipes in the swale bottom occur at depths where the water table often fluctuates into and around the pipe zone. As the winter progressed, the piezometers responded more rapidly to larger rain events. This behavior supports the findings of Ziemer and Albright (1987) who observed a strong dependence of pipeflow on soil moisture conditions. Piezometric responses in undisturbed drainages will generally mirror pipeflow responses because both are dependent on flow through macropores. Soil pipes are simply the largest size-class of macropores. The peak piezometric response was noted for a mid-February 1994 storm with peak rainfall occurring over an 18-hr period (*fig. 5*). Piezometric responses on the two side-slope transects were fairly similar to each other. The lag between the rainfall and the peak piezometric response for A and C transects

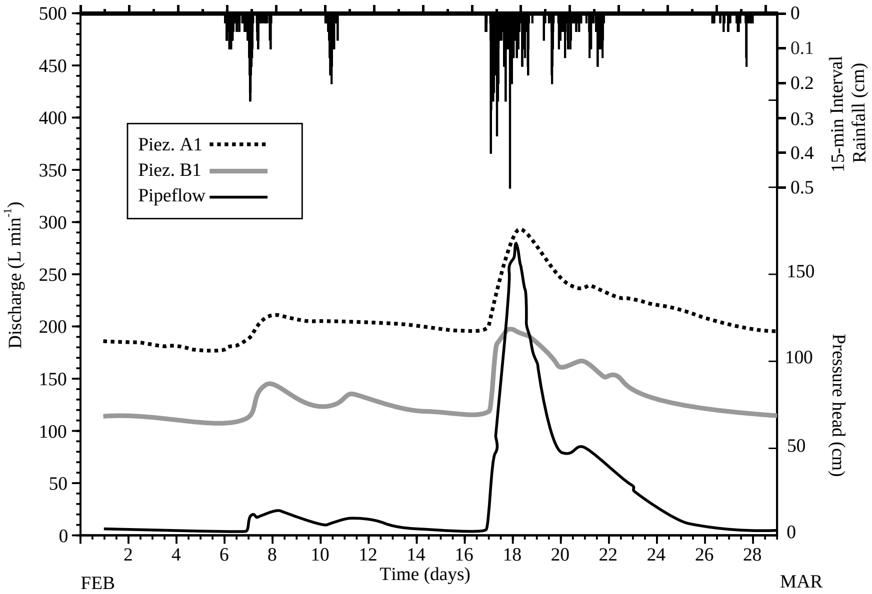


Figure 5—M1 pipeflow and piezometric response to a moderate storm event during February 1994. Note the similarity between pipe discharge and subsurface pore pressures responses to this discrete storm event.

generally exceeded the lag for the B-nest piezometers. The convergence of flow in the B subswales could explain the difference in lag times with the parallel side-slopes.

K2 Pore Pressures

The post-treatment response along two transects (C and E) has been evaluated through hydrologic year 1993. Regression analysis results indicate increased peak piezometric responses after logging. All six postlogging regressions were significantly different than the prelogging regressions ($p < 0.05$). The postlogging intercept terms were greater than the prelogging coefficients and, in some cases, the slopes of the postharvest regression lines were reduced (*fig. 6*). Unlike the stream discharge peaks (Ziemer, these proceedings) and the pipeflow peak response just described, increases in peak pore pressures were detectable for both large and small storms, as well as for antecedent moisture conditions ranging from a relatively dry to a fully saturated soil profile. Between storms, piezometric water levels remained higher in the postharvest period than before harvest. Sidle and Tsuboyama (1992) state that pore pressure responses tend to be less variable at the base of the hillslope than at upslope positions because of higher soil moisture content and the presence of preferential pathways in the saturated zone. These K2 data support that hypothesis. Greater variation and larger magnitude increases were observed in the upslope piezometers (C3P2 and the E transect). At the mean M106 peak discharge, pore pressures were 9 to 35 percent greater than those predicted by the preharvest relationship.

E-Road Pore Pressures

With only a single year of pretreatment data, regression analysis was only marginally successful in illuminating changes in pore pressure response at the E-road site. Before road construction, pore pressure responses at this site were minimal. Although the bore holes for the two most upslope piezometers were the deepest installations at this swale (5.7 and 7.7 m, respectively), positive pore pressures were not detected before road building and tractor logging. During the first winter after road building, these upslope piezometers remained dry; however, some changes were observed at the lower instrument sites (R1P2 and R2P2). There were brief spikes in pore pressures of less than 0.5 m, reflecting individual precipitation events superimposed on a more extended pore pressure response of about half that magnitude indicative of seasonal effects (*fig. 7*). Hydrologic year 1991 was also the second-driest year on record at Caspar Creek, with annual precipitation totaling only 716 mm. This lack of rainfall made first-year changes difficult to detect.

After tractor logging was completed late in 1991, a series of normal and above-normal rain years ensued. The event-driven pore pressure spikes continued at R1P2 during 1992 and 1993. The regression analyses of the predisturbance pore pressure peaks on the M106 peak pipeflows ($\log_{10}$) were fairly successful at explaining the variations in response at the downslope installations both before and after logging. The r^2 values for the prelogging regressions were greater than 0.80 for R2P2 and R3P1, and 0.49 for R1P2. Similar r^2 values resulted from the postlogging regressions of these piezometer peaks. The postlogging regressions indicate increased peak pore pressures at R1P2, R2P2, and R3P1 that are similar to those observed at the K2 site (*fig. 6*). However, there was no significant relationship between peak pipeflow at M106 and the pore pressure response at the upslope E-road piezometers. These results suggest the upslope E-road pore pressure response was quite different than

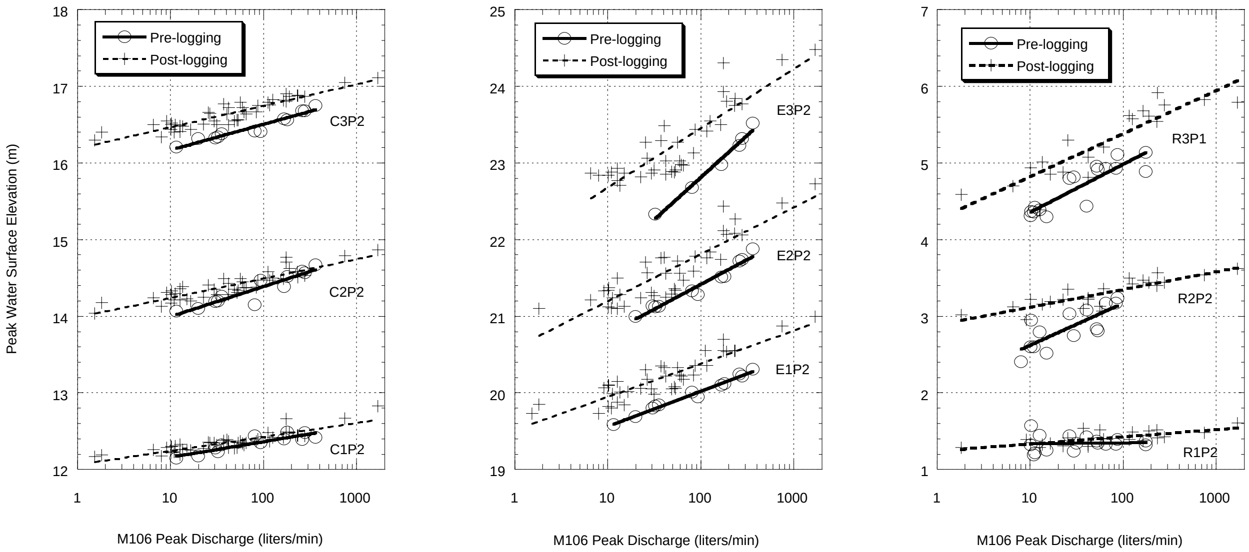


Figure 6—Regression comparisons of peak piezometric response at the K2 and E-road sites before and after clearcutting. C1P2, C2P2, and C3P2 are located in the lower portion of the K2 slope. E1P2, E2P2, and E3P2 are mid-slope K2 locations. R1P2, R2P2, and R3P1 are located along the E-road swale axis between pipeflow outlet and the new road. Elevations are relative to the pipeflow outlet at each swale.

the response below the road and the response in the undisturbed M1 swale.

However, after road construction and logging, a clear and dramatic increase in pore pressure response at the above-road installations is evident. Not only did peak pore pressures increase in response to a discrete storm event, but also there was a progressive increase in piezometric water levels related to cumulative seasonal precipitation (*fig. 8*). At R4P2, the dry-season recession was particularly slow. By late fall of 1994 and 1996, the pore pressure level remained higher than it had been at the onset of the preceding hydrologic year. Pore pressures at this bedrock installation located directly under the road centerline have yet to return to predisturbance levels. At this same location, a second piezometer, installed at the time of road construction at the interface between the fill and the original ground surface, never showed a positive pressure response. However, this pressure transducer failed in 1996 and was not replaced.

For all installations at the E-road site, the post-road construction and logging annual pore pressure peaks exceeded the predisturbance annual peak (*table 1*). To explore this difference, a variable reflecting the storm rank through all years (1990 to 1995) was evaluated. This regression was more significant in explaining the peak responses at R5P2 ($r^2 = 0.23$) and R6P2 ($r^2 = 0.61$), but not significant for the below-road installations. Above the road, the apparent trend in pore pressures levels is one of increased peak levels over time since logging (*fig. 9*). However, this may be a reflection of above-normal rainfall totals in 1993 and 1995, rather than the isolated impact of road construction in this swale. More work remains to be done to model the pore pressure response at this E-road site. Pipeflow data from this site has yet to be evaluated. This future analysis will provide an important indication of the integrity of the macropore flow mechanism at this site after road construction and tractor logging.

Conclusions

Subsurface flow is the dominant process by which rainfall is delivered to stream channels in the coastal redwood region. Several different flow paths exist within soils and bedrock, and they interact on both rain-event and seasonal time scales. As the soil and subsoil become saturated, the soil pipes play an extremely important role in hillslope drainage. The combined water storage and transmissive properties of shallow earth materials are such that headwater watersheds produce significant storm runoff and dynamic changes in fluid pressures that are an important factor in the stability of hillslopes. Management activities such as timber harvesting and road construction can alter the subsurface flow and pore pressure response to rain events. Increased subsurface flow from the loss of rainfall interception and transpiration after timber harvesting increases peak pipeflow and may accelerate scour erosion within the soil pipes. This form of subsurface erosion can lead to the expansion of discontinuous gullies within the unchanneled swales and increased sediment loading to surface channels such as has been observed in some of the Caspar Creek cutblocks (Ziemer 1992; Lewis, these proceedings). Further, subsurface drainage may be impeded by the felling and yarding of logs in these zero-order swales if matrix and macropore flows are reduced by soil compaction or shallow pipe collapses, thus accelerating gully erosion.

Timber harvesting increases peak pore pressures, but whether these fluid pressures pose significant risks to slope stability is highly

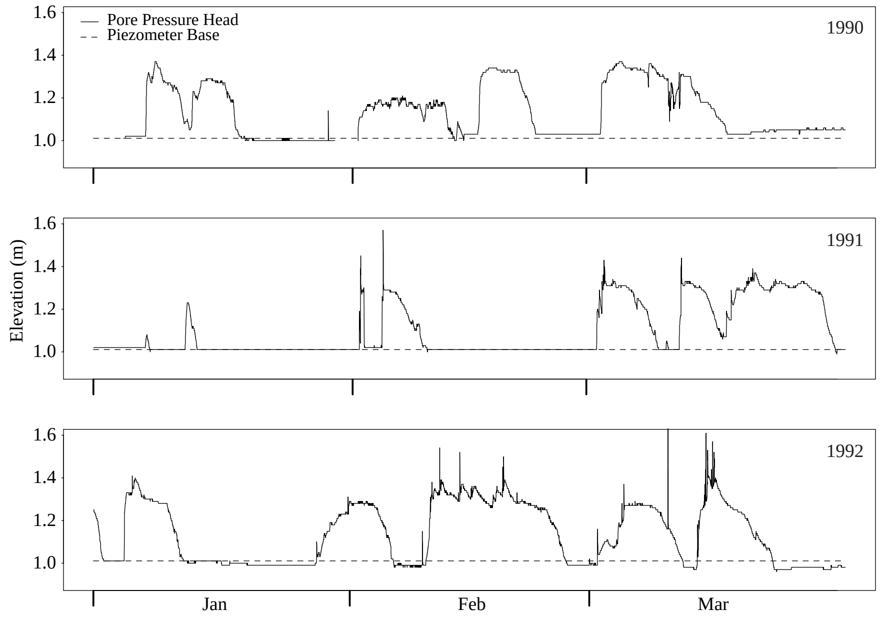


Figure 7—Piezometric response at the E-road site (between the base of the road fill and the pipeflow outlet) for three winter periods: 1990 (predisturbance), 1991 (post-roadbuilding) and 1992 (postlogging). Elevations are relative to the pipeflow outlet.

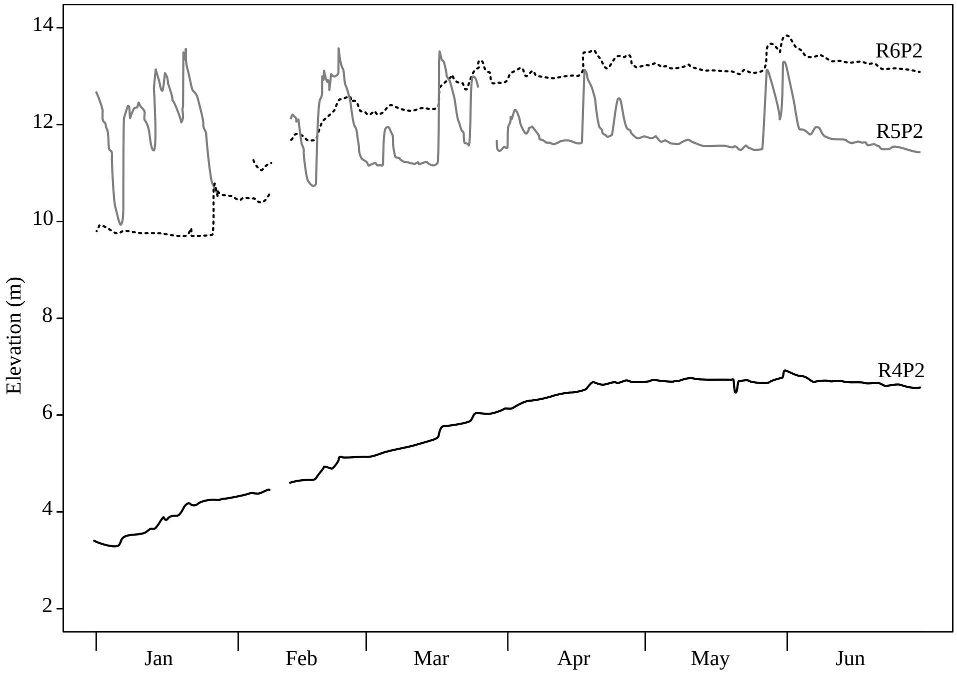


Figure 8—Upslope piezometric response at the E-road site after road construction and tractor logging. Note the seasonal increases in pore pressure heads as the rainy season progresses and the discrete storm response most evident at R5P2. Elevations are relative to the pipeflow outlet. Gaps in traces indicate missing data.

***Table 1**—Annual maximum pore pressures (m) at E-road piezometers. Road constructed in May 1990 with road centerline at R4P2. Tractor logging of swale occurred September through October 1991. "NR" indicates that no positive pressure head was observed during that year. Base elevation (m) is the bottom of piezometer well relative to the elevation of the pipeflow outlet. Maximum pore pressures for all years are shown in bold.*

Hydrologic Year	R1P2	R2P2	R3P1	R3P2	R4P2	R5P2	R6P2
1990	0.37	1.31	0.89	2.11	0.77	NR	NR
1991	0.57	1.71	0.86	3.39	0.63	NR	NR
1992	**0.65**	1.91	1.37	**6.05**	**6.03**	2.97	6.45
1993	0.61	2.09	1.67	4.24	4.61	4.77	4.18
1994	0.42	**2.12**	1.65	4.29	3.89	3.97	6.56
1995	0.52	1.92	**1.84**	4.50	5.25	4.72	**7.49**
1996	0.46	1.88	1.81	4.49	4.69	4.84	6.76
1997	0.45	1.80	1.84	5.59	4.07	**4.93**	6.04
Maximum Pore Pressure (m)	**0.65**	**2.12**	**1.84**	**6.05**	**6.03**	**4.93**	**7.49**
Hole Depth (pre-road) (m)	1.37	2.59	1.96	4.80	7.66	5.69	7.83
Base Elevation (m)	1.00	1.53	4.25	1.57	2.29	8.79	9.64

dependent on local hillslope conditions. At those sites most prone to failure because of inherent geologic and soil conditions, timber harvest activities may tip the delicate balance of hillslope stability towards failure. However, such failures are expected only in response to relatively extreme rainfall events occurring at roughly 5-year return periods (Cafferata and Spittler, these proceedings). Thus far, the data from the North Fork phase of the Caspar Creek study suggest that the frequency of large landslides has not increased owing to the timber harvest activities between 1989 and 1991. The road location and design used in the North Fork logging demonstrate a tremendous improvement in the application of the principles of subsurface hydrology to minimize the risks of aggravating slope instabilities. However, it is too early in the post-harvest history to draw definitive conclusions concerning slope stability. Large landslides occur relatively infrequently; thus, it is necessary to evaluate failure rates over a long time. One caution suggested by the findings in the M1 swale and previous research is that convergent topography will amplify pore pressure responses and there should be special attention and analysis when planning operations in these areas. Designated crossings are an effective safeguard, provided that the designator understands the principles of subsurface hydrology as they relate to erosion control. Road construction can have a very significant impact on the timing and magnitude of pore pressure responses as exemplified by the E-road

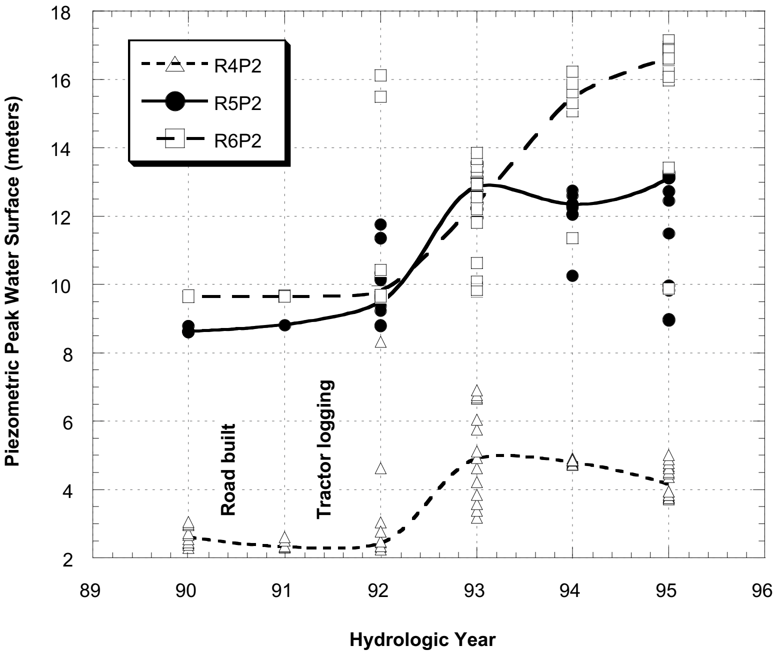


Figure 9—Peak pore pressure response upslope of the new road at the E-road site. Fitted lines connecting median pore pressure peaks suggest a trend of increased pore pressures over the 6-year period since road construction. Elevations are relative to the pipeflow outlet.

site. Additional work is needed to further elucidate more general relationships between road construction and pore pressure evolution, as well as to better understand site-specific subsurface conditions as they affect slope stability.

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