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Effect of logging on subsurface pipeflow and erosion: coastal northern California, USA

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Abstract Three zero-order swales, each with a contributing drainage area of about 1 ha, were instrumented to measure pipeflows within the Caspar Creek Experimental Watershed in northwestern California, USA. After two winters of data collection, the second-growth forest on two of the swales was clearcut logged. The third swale remained as an uncut control. After logging, peak pipeflow was about 3.7 times greater than before logging. Before logging, little sediment was transported through the pipes. Suspended sediment concentrations before logging were less than 20 mg l^{-1} and coarse-grained sediment was rare. After logging, there was great spatial and temporal variability in sediment transport. Sediment loads increased dramatically from some pipes during some storms, but from other pipes, sediment discharge remained unchanged after logging.

INTRODUCTION

Soil piping was originally an engineering term used to describe concentrated subsurface erosion of dams and levees caused by seepage force under a positive hydraulic head (Terzaghi & Peck, 1948). Some of the first work to consider the importance of piping to subsurface water transport in natural slopes was undertaken by Whipkey (1967, 1969) and Aubertin (1971). Both of these authors studied piping in the Allegheny-Cumberland Plateau region in the east-central United States. Whipkey and Aubertin both concluded that piping raised the overall hydraulic conductivity of soils and that macropores rapidly intercepted and routed subsurface water. Subsequently, piping in natural landscapes has been observed in highly varied settings, ranging from arid to humid regions and greatly differing geological and vegetative conditions throughout the world (Baillie, 1975; Jones, 1981).

Elevated pore water pressures caused by inefficient subsurface water drainage are a primary cause of large mass erosion events. Where subsurface piping networks exist, matrix interflow can be captured and efficiently routed to surface channels downslope. The result can be reduced pore water pressures and lowered landslide risk. However, large hydrostatic forces can develop rapidly and cause a slope failure if the pipe network is discontinuous (Sidle, 1986) or water flow within the pipe is retarded by a constriction or collapse (Tsukamoto *et al.*, 1982).

Piping can be responsible for accelerated subsurface sediment transport. Subsurface piping pathways can extend for some distance as either continuous features or as a system of interconnected features that form extensive, branched networks. As the pipe enlarges, flow in the conduit becomes increasingly concentrated and turbulent. Collapse of these subsurface conduits and networks can lead to the development of karst-like ("pseudokarst") topography (Halliday, 1960) and the development of gully networks (Higgins, 1984; Swanson *et al.*, 1989).

Soil piping is an important, but little studied, basic hydrologic and geomorphic process in forested steeplands. Piping must be understood in order to design for environmentally sound land use.

STUDY AREA

The study area is located at 39°21′N 123°43′W, about 7 km from the Pacific Ocean in the headwaters of the North Fork Caspar Creek Experimental Watershed, in the Jackson Demonstration State Forest near Fort Bragg, California, USA. The topography is youthful, consisting of uplifted marine terraces that date to the late Tertiary and Quaternary periods (Kilbourne, 1986). Hillslopes are moderate, ranging from 30 to 70%. The elevation of the study area ranges from 100 to 320 m.

The soils within the study swales are classified as the Vandamme soil series, a clayey, vermiculitic, isomesic typic tropudult, derived from sedimentary rocks, primarily Franciscan greywacke sandstone (Huff *et al.*, 1985). The Vandamme soil series is characterized as being well-drained with moderately slow permeability. The depth to paralithic contact is generally 100 to 150 cm. The soil contains 35 to 45% clay with about 10% gravel.

Overstory vegetation is dominated by dense stands of 100-year-old second-growth Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) and coast redwood (*Sequoia sempervirens* [D.Don] Endl.). Stem volume averages about 700 m^3 ha^{-1}. Understory vegetation includes evergreen huckleberry (*Vaccinium ovatum* Pursh), Pacific rhododendron (*Rhododendron macrophyllum* D.Don), and sword fern (*Polystichum munitum* [Kaulf.] Presl.). Most of the original old-growth timber was removed by clearcut logging operations in the late 1800s. Since that time, the North Fork watershed has remained largely undisturbed.

The climate is characterized by low-intensity rainfall, prolonged cloudy periods in winter, and relatively dry summers with cool coastal fog. Mean annual precipitation at Caspar Creek is approximately 1190 mm, with 90% occurring between October and April. Snowfall is rare. Temperatures are mild due to the moderating effect of the Pacific Ocean.

Piping is common in the uppermost portion of the Caspar Creek basin. Pipe outlets are commonly found in gully headwalls or along the banks of perennial and ephemeral channels. Open channel flow predominates where drainage areas are greater than about 20 ha. For smaller basins, discontinuous gully features are often formed by the collapse of the ground surface into intact and hydrologically active pipes. Between collapsed portions, pipeflow continues through intermediate land bridges of varying lengths. Along the axes of swales smaller than about 2 ha, there is little evidence of surface runoff, except for an occasional pipe outlet to the surface. Such pipe outlets often discharge appreciable amounts of water and sediment during rain storms, and may have sediment aprons near the outlet. Usually the water will re-enter the soil a short distance downslope from such outlets.

METHODS

Three zero-order swales (M, K1, K2), each with a contributing drainage area of about 1 ha, were instrumented in 1987 to measure pipeflows (Fig. 1). Soil pipes were exposed by trenching or enlarging existing collapse features (Ziemer & Albright, 1987). The discussion of methods is summarized from Albright (1991).

Water flowing from each pipe was captured by driving angular or circular-shaped metal flashing into the soil face around the soil pipe. The metal flashing was secured using a concrete mixture applied to a wire mesh framework surrounding the flashing and pinned to the trench wall. The captured flow from each pipe was routed through a plumbing network into PVC pipe containers, 15 cm in diameter and 100 cm tall. Containers were mounted upright in the excavation, with the base end capped and the upper end open. Drainage holes and/or slots were cut in a pattern lengthwise along the side of the container. Each container was calibrated in the laboratory, with additional calibration points taken in the field, to allow derivation of individual stage-discharge relationships.

A pressure transducer, mounted in each container, monitored water head. Transducer readings were recorded at 10-min intervals in a digital data logger

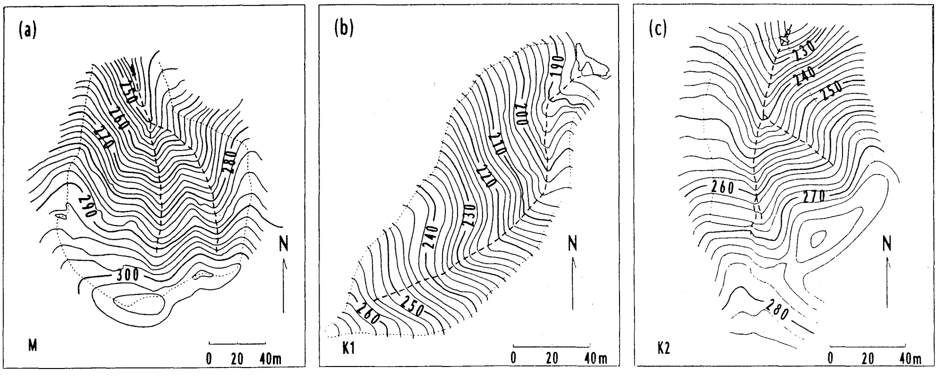

Fig. 1 Topography of study swale: (a) M, (b) K1, and (c) K2.

located at each site. In addition to pipeflow, provision was made to monitor any overland flow and matrix seepage through the soil horizons.

A sediment pouch was placed at the top of each discharge container to collect coarse sediment particles and organic debris. The sediment pouch was constructed of stainless steel wire screen having a 1 mm mesh. Periodically, the pouches were emptied and the sediment was oven-dried and weighed. If the sample weighed more than 50 g, the sediment was sieved to determine the particle-size distribution. Suspended sediment was collected using a pumping sampler.

Rainfall, piezometric level, soil water tension, and downstream channel discharge were also measured (Ziemer & Rice, 1990).

Pipes exposed in the excavated headwalls did not occur at any consistent level or position, but all were within the approximately 2-m deep soil profile. Pipe discharges measured at the three sites during storm runoff varied from steady dripping in some pipes to a peak of over 10 l s^{-1} in others.

The M piping site is located in the central axis of a 1.69-ha swale (Fig. 1(a)), at the upper end of a gully that marks the beginning of channelized surface discharge. Pipe discharge measured at this excavation includes pipe M106, an approximately 80 cm high by 60 cm wide pipe at its exposure in the trench face. This pipe provides at least 90 percent of pipe discharge from this swale during storm runoff. M106 is a perennially discharging pipe, although summer baseflow often declines to less than 0.01 l s^{-1}. The base of pipe M106 is nearly 2 m below the ground surface and is at an interface between the upper soil material and a lower gleyed-clay layer. Site M also has a cluster of small (2 to 4 cm) pipes in close proximity about 0.5 m below the ground surface that were collectively measured as pipe M190. Finally, metal flashing and discharge measuring equipment was installed at the M site to separately monitor any overland flow that might occur down the swale axis, as well as matrix seepage through a wedge of colluvium found near the ground surface.

The K1 piping site is located along one side of the axis of a 1.04-ha swale (Fig. 1(b)). This site is positioned at a gully headwall that had three natural terraces. Hydrologically active pipes occur along the upper two terrace levels. Pipes at this site include K101, a flashy, ephemeral pipe about 1.5 m deep in the soil profile on the middle terrace. Pipe K102, the pipe having the largest discharge at site K1, is located on the same terrace as, and immediately adjacent to, K101. Like M106, K102 maintains a baseflow during much of the winter rainy season, although pipeflow in K102 ceases before M106 during extremely long and dry summers. Pipes K105 and K107, located within 0.5 m of the ground surface on the upper terrace, are ephemeral pipes that are flashy during storm events. Other pipes present at site K1 were not measured on a regular basis, but did not appear to provide significant storm discharge during the 4-year study period. All pipes at the K1 site are between 10 to 20 cm in diameter, and all pipe outlets are within the soil profile.

The K2 piping site is located along the axis of a 0.83-ha swale (Fig. 1(c)). A 2-m deep trench was excavated across the swale through a previously undisturbed swale floor. There are three pipes at the K2 site. K201 is approximately 50 cm in diameter, and is located about 1.5 m below the ground surface. A mixed clay and broken shale layer is located about 0.5 m below the outlet of K201 in the trench face. K201 is the largest pipe and is similar to M106 and K102 in that it maintains a baseflow for extended periods during the dry summer. Baseflow at K201 ceases after K102, but before M106. K202 is a pipe adjacent to K201, at about the same depth, but it is approximately half the size. Pipe K202 has a subdued response during storm events and maintains a trickle base flow during much of the time that K201 has a baseflow. Finally, pipe K203 is about 15 cm in diameter and is located 0.5 m below the ground surface. Pipe K203 is ephemeral, but very flashy during storm events.

After two winters of data collection in the three swales, all of the trees in two of the swales (K1 and K2) were felled and removed by cable yarding in August 1989. The use of heavy logging equipment was expected to compact the soil, reduce infiltration rates, and increase surface runoff. In addition, heavy equipment might collapse some of the subsurface pipes, increasing local pore water pressure and the chance of landslides (Sidle, 1986). Consequently, heavy logging equipment was excluded from the hillslopes of the logged swales and was restricted to specific locations on the ridges.

The third swale (M) was kept unlogged as a control to evaluate changes in pipeflow occurring in the two logged swales.

OBSERVATIONS AND DISCUSSION

Pipeflow

Pipeflow accounted for virtually all of the storm flow from the three swales. There was no surface channel flow and no near-surface flow through the colluvial wedge. There was a small amount of matrix seepage through the excavated trench face during storms, but this would account for less than 1% of the total discharge. Tsukamoto *et al.* (1982) reported similar results from pipes in an excavated trench in a small forested basin in Japan. Swanson *et al.* (1989) reported that during a 25-year recurrence-interval storm, nearly 70% of the water was discharged through the subsurface piping (tunnel) network within a 50-ha coastal drainage in central California. Peak water discharge from the one of their major pipes was about 5 l s^{-1}. Jones (1987) reported that pipeflow is responsible for 49% of the stream storm flow from the peaty Maesnant catchment in mid-Wales, UK.

Peak pipeflow increased after logging swale K2 ($p < 0.0001$) to about 3.7 times greater than that expected before logging, based on the flow observed in unlogged swale M (Fig. 2(a)). Chow's test (Wilson, 1978) was used to detect differences between regression lines. The data suggest that the first several storms during autumn 1989, immediately after logging, produced larger peak flows than had been observed before logging. However, one year later,

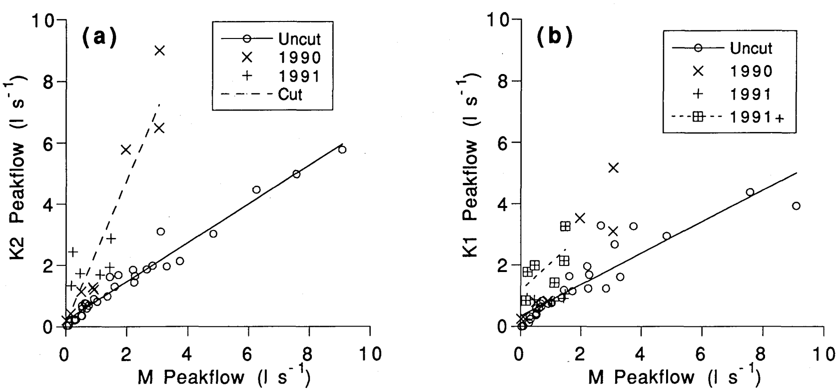

Fig. 2 Relationship between peak pipeflow in uncut control swale M and swales (a) K2 and (b) K1 before and after logging was completed in August 1989. For K1, 1991+ indicates the sum of pipeflow from site K1 and that from a new outlet about 30 m upslope.

in autumn 1990, the first storms produced even larger peak flows in the logged swales than did those in autumn 1989, for comparable peak flows observed in the unlogged swale. Before logging, transpiration, and consequent soil moisture depletion, in the unlogged control swale and in the swales scheduled to be logged can assumed to be similar. Logging occurred in August 1989, near the end of the dry summer period. The first significant rain occurred in November 1989, but the soil moisture in both logged and unlogged swales had already been depleted by transpiration to near the annual low by the time the areas were logged in August. Consequently, the difference in pipeflow between logged and unlogged swales in response to rainfall in autumn 1989 would reflect only the small differences in soil moisture that developed after logging (i.e. during September and October), plus differences in canopy interception loss. In contrast, at the end of summer 1990, evapotranspiration-related differences in soil moisture depletion between the logged and unlogged areas accumulated during the entire 6-month rainless summer period. When rains began in autumn 1990, soil water recharge was more rapid in the logged area because of a smaller end-of-summer soil moisture deficit, reduced canopy interception of rainfall, and reduced transpiration between storms.

At swale K1, the peak pipeflow response to logging appeared to be quite different than at swale K2. Peak pipeflow from the pipes measured in the logged swale K1 in 1991 was not significantly different ($p = 0.937$) from the unlogged swale M (Fig. 2(b)). However, in 1990, pipeflow began to emerge from an outlet about 30 m upslope from the instrumented K1 site. Before logging, this outlet had been observed to flow rarely and only with a small discharge during the largest storms. Flow from this outlet became an increasingly common occurrence after logging and the discharge has been measured since mid-winter 1990. When the measured discharge from this new outflow pipe is added to the pipeflow from the other pipes at K1, the relationship between peak pipeflow at the two logged swales (K1 and K2) is not significantly different before or after logging ($p = 0.558$). That is, comparable peak flow increases occurred at both K1 and K2 after logging. The exact nature of the interconnection of the pipes at K1 with the upslope outlet is not yet clear, but it appears that the relative importance of this feature increases with total peak discharge.

Ziemer (1981a) found that logging the adjacent 508-ha South Fork Caspar Creek watershed increased peak streamflow for only the smallest 25% of the storms, with the early autumn storms exhibiting the greatest increase after logging. Logging the South Fork did not significantly affect streamflow during larger storms. The pipeflow data collected to date do not suggest a similar pattern in the logged swales. So far, there is no indication of a reduction in logging effect during larger storms as found in the South Fork. There are several possible explanations:

(a) The storms that have occurred since logging have generally been separated by several months of dry, mild weather. This weather pattern can maximize differences between logged and unlogged sites by allowing differences in soil moisture deficit caused by winter transpiration and canopy interception to develop.

(b) No major storms have been measured to date. A large storm at the end of May 1990 overwhelmed the plumbing systems in both the logged and control swales and the peak flow data were lost.

(c) The catchment size is different. The South Fork catchment is 508 ha and the swales are about 1 ha. Smaller catchments are often more responsive to forest cutting.

(d) The logging was different. In the South Fork, 60% of the forest volume was cut and trees were tractor yarded. The swales were clearcut and cable yarded.

Additional data are needed to clarify the effect of logging on peak pipeflow during large storms.

Sediment

Before logging, very little sediment was transported by the pipes at Caspar Creek. The suspended sediment concentrations from all pipes were less than 20 mg l^{-1} (Fig. 3). Seldom would the screen pouches in the discharge containers contain more than a few grains of coarse sediment. Usually less than a gram of material would accumulate during any 2-week period. During a large storm in March 1989, pipe K101 deposited 634 g of sediment in the screen pouch, K201 produced 168 g, and M106 had 17 g.

After logging, sediment discharge from some of the pipes increased. A comparison with data collected from unlogged control swale M (Fig. 3(a)) suggests that logging did not increase the concentration of suspended sediment transported by the pipes at swale K1 (Fig. 3(b)). However, it is difficult to separate the effect of logging from the large natural variability of sediment

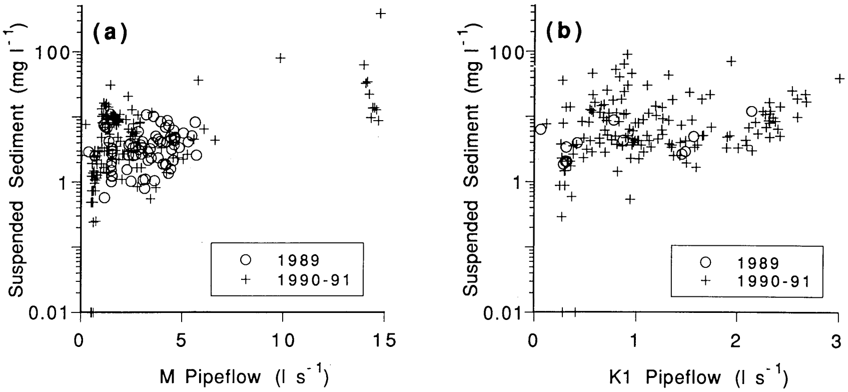

Fig. 3 Relationship between suspended sediment concentration and pipeflow at uncut control swales (a) M and (b) K1 before and after logging was completed in August 1989.

transport within the piping system. In addition, there were only a few storms measured before logging.

Logging appears to have increased the movement of coarse sediment, at least during the first important storm after logging. During the 8 January 1990 storm, the sediment pouch in pipe K101 caught 2800 g of coarse sediment, while the unlogged pipe M106 caught less than 1 g. During the 1 February storm, K101 caught 26 g, while M106 caught none. In contrast, during the late May 1990 storm, the sediment pouch in K101 contained 90 g, while that in unlogged M106 contained 537 g, the maximum observed from swale M during the study period. During all other periods in the two years after logging, the sediment pouches contained less than a gram of sediment for all pipes, except pipe K201. This pattern of sediment increase in K101 implies that small segments of the roof or wall were loosened by local ground shaking caused by the impact of the felled trees, and that the first storm flows after logging transported this material through the pipes.

Sediment discharge from pipe K201 increased dramatically (Fig. 4). Two medium-sized redwood trees were left within about 5 m of the piping site to minimize the risk of destroying the instrumented site by an error when felling and yarding the trees. During a moderate storm on 8 January 1990 storm, a large quantity of sediment began to be discharged from K201. The sediment pouch filled quickly and the plumbing became clogged with large amounts of sediment. An estimated 500 kg of sediment was discharged from the pipe during this storm. A month later, on about 1 February 1990, one of the residual trees located immediately above the piping site toppled during a small rain storm. When the tree fell, the root system displaced some soil and exposed a subsurface cavern having a volume of about 1 m^3 connected to pipe K201. The early sediment discharge and delayed tree fall implies that the tree was first undermined by pipe erosion. In late May 1990, a large storm destroyed the plumbing that connected pipe K201 to the instrumentation. The cavern

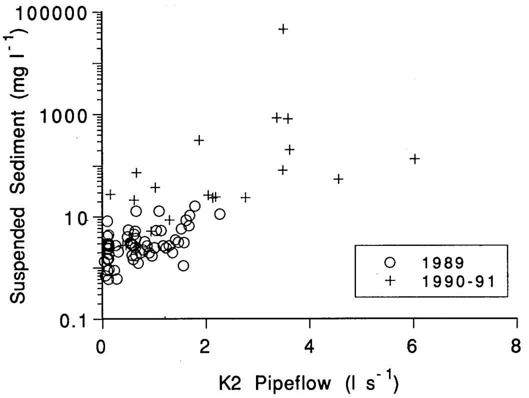

Fig. 4 Relationship between suspended sediment concentration and pipeflow at swale K2 before and after logging was completed in August 1989. In February 1990, a tree toppled immediately above the K2 instrument site.

under the fallen tree expanded up the swale about 2 m, forming a small incipient gully. On 22 May 1990, K201 produced a suspended sediment concentration of 46 500 mg l^{-1}. About 2500 kg of coarse sediment was transported by K201 during this storm before the plumbing could be reinstalled. The amount of coarse sediment was estimated from the enlargement of the gully above K201 and the volume of sediment deposited below the piping site. In 1991, several additional sections of the gully wall collapsed, but only 2.7 kg of coarse sediment were moved by pipeflow to the instrumented site during the entire winter. The gully will probably continue to expand during future storms.

The coarse sediment caught in the pouches was dried and sieved to determine the distribution of particle sizes. About 30% of the sediment was greater than 4 mm in diameter, and about 5% was greater than 16 mm. About 25% of the sediment passed through a 1 mm diameter sieve. By the nature of the position of the 1-mm mesh sediment pouch in the discharge containers, the sediment remaining in the bags was well-washed when collected. It is reasonable to surmise that most of the sieved sediment passing the 1 mm sieve was derived from larger soil aggregates that were broken by sieving. Logging did not appear to have changed the distribution of particle sizes.

Swanson *et al.* (1989) reported that piping and subsurface erosion were the primary mechanisms responsible for the development of gully networks on a 50-ha coastal drainage in central California. During a 25-year recurrence-interval storm, nearly 70% of the water and over 90% of the sediment was discharged through the subsurface piping (tunnel) network. Suspended sediment concentrations at the pipe outlets measured by Swanson *et al.* (1989) during this storm averaged 17 800 mg l^{-1}. Peak water discharge from one of their major pipes was about 5 l s^{-1}. Jones (1987) reported that pipeflow is responsible for 49% of the stream storm flow and about 15% of the annual sediment yield from the peaty Maesnant catchment in mid-Wales, UK. He concluded that sediment yields from high discharge pipes were well-correlated with pipe length and contributing drainage area. Jones (1987) found a good relationship between the weekly sediment discharge from pipes and volume of flow exceeded 5% of the time during the week.

Episodic erosion events are typical for sediment transport by pipes. Large spatial and temporal variability in sediment transported from pipes has been observed elsewhere by Swanson *et al.* (1989) and Jones (1990). Much of the time the piping network serves as a stable conduit of water and sediment. Periodically, however, a piece of wall or roof will become weakened and collapse into the pipe, creating an abundance of soil to transport. Occasionally, the pipe might become plugged, causing a rapid increase in local pore water pressure, and result in a landslide (Tsukamoto *et al.*, 1982; Sidle, 1986).

It may still be too early to see the consequences of logging on pipe sediment at Caspar Creek. As time progresses, local soil strength should decrease as the root system decays and adjusts to the reduced above-ground live biomass. Total root biomass has been found to reach a minimum about 10 years after cutting a redwood forest (Ziemer, unpublished data). Numerous studies have reported the relationship of declining root biomass and soil strength with increased and delayed slope failures after timber cutting (Ziemer, 1981b). Longer-term monitoring will be required to determine the magnitude and timing of sediment transport from these pipes after logging.

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