

Subsurface pipeflow dynamics of north-coastal
California swale systems

ROBERT R. ZIEMER & JEFFREY S. ALBRIGHT
USDA Forest Service, Pacific Southwest
Forest and Range Experiment Station,
Arcata, California 95521, USA

ABSTRACT Pipeflow dynamics are being studied at Caspar Creek Experimental Watershed in north-coastal California near Ft. Bragg. Pipes have been observed at depths to 2 m within trenched swales and at the heads of gullied channels in small (0.8 to 2 ha) headwater drainages. Digital data loggers connected to pressure transducers monitor discharge using calibrated standpipes. During storms, pipeflow up to 8 l s^{-1} has been measured, while, within the same swales, no surface channel flow occurred. Pipeflow discharge has been correlated with antecedent precipitation.

INTRODUCTION

Most of the geomorphic literature attributes drainage network evolution, except in karst areas, to surface runoff processes. Recently, the influence of near-surface groundwater flow in promoting subsurface erosion in non-karst areas and the development of drainage networks has received increasing attention (Higgins, 1984). The geomorphic features resulting from erosion by the flow of subsurface water in non-calcareous rocks have been referred to as "pseudokarst" (Walladay, 1960; Parker *et al.*, 1964).

In arid regions, the role of piping in gully development has been recognized for some time. In humid regions, however, the geomorphic significance of piping was largely overlooked until Kirkby & Chorley (1967) presented a model of soil water throughflow and saturated overland flow as an alternative to Horton overland flow on vegetated slopes.

Under favorable conditions, subsurface drainage can promote accelerated erosion by chemical (solution), physiochemical (suffusion), and physical (piping and landsliding) processes. Biological processes generate organic acids that accelerate the dissolution of primary soil minerals and also disperse secondary minerals (Durgin, 1984). These minerals can be transported through the soil, and eventually to a stream channel, by subsurface drainage. As chemical erosion progresses and the soil becomes more porous, water flowing through the soil can detach and move colloids through soil pores—a process called suffusion. Suffusion can lead to soil piping as progressively larger material is eroded.

In addition, stress fractures in the soil, as well as biotic activity by invertebrates and vertebrates and by root networks may

contribute to the initiation and subsequent development of piping systems.

Water infiltrates the pipe as laminar flow, but within the pipe, flow becomes turbulent and erosion is primarily by corrosion and undermining of pipe walls (Dredge & Thorn, 1976). As subsurface erosion continues, pipe roofs may collapse, forming pseudokarst topography. Goldsmith & Smith (1985) summarized the conditions essential for piping: (a) a source of water, (b) a surface infiltration rate that exceeds the subsurface permeability at some depth, (c) a zone of potentially dispersive soil, (d) a hydraulic gradient to cause water to flow, and (e) an outlet for the lateral flow.

METHODS

Study area

The study is located near the headwaters of the North Fork Caspar Creek Experimental Watershed on the Jackson Demonstration State Forest. The 508-ha watershed is approximately 10 km south of the city of Fort Bragg, California (Fig. 1).

The dominant aspect of the watershed is south-southwest. The elevation ranges from 37 to 320 m. Topographic development of the area is youthful, with uplifted marine terraces deeply incised by antecedent drainages. Slopes are moderate, ranging from 30 to 70%, being steepest near the stream channel and becoming more gentle near the broad, rounded ridgetops.

The soil at the study sites is composed of the Vandamme soil series a soil derived from sedimentary rocks of the Cretaceous Age (California Department of Forestry, 1985). This series accounts for

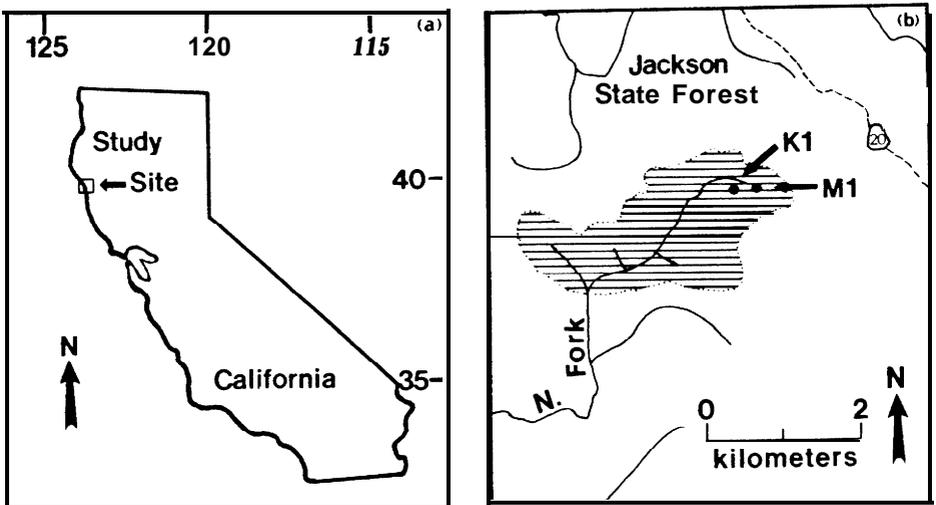


FIG.1 North Fork of Caspar Creek: (a) location, (b) piping sites.

approximately 40% of the North Fork watershed, and is found along the ridges and upper slopes. The depth to paralithic contact is typically 100 to 150 cm. It is a well-drained soil formed in material weathered from sandstone and mudstone. The particle-size averages from 35 to 45% clay. Gravel content ranges from 0 to 10%. The Cr horizon is highly weathered saprolitic sandstone and mudstone that slakes in water. The soil shows a mixed mineralogy with moderate amounts of kaolinite and vermiculite (Rittiman, personal communication). The infiltration capacity of the Vandamme soil is very slow and the rate of water transmission through the subsoil is moderately slow.

The climate of the study site is typical of coastal northern California. The fall and winter seasons are characterized by a westerly flow of moist air which typically results in low-intensity rainfall and prolonged cloudy periods. In the winter, the southerly position of the north Pacific subtropical anticyclone allows frequent storms to enter the region, but in the spring this weather system migrates northward and rainfall is much less frequent. Summers are relatively dry with cool coastal fog.

Temperatures are mild with muted annual extremes and fairly narrow diurnal fluctuations due to the moderating effect of the Pacific Ocean. Mean January temperature is about 10°C and mean July temperature is about 13°C. The frost-free season is 290 to 365 days.

Mean annual precipitation at Caspar Creek is approximately 1190 mm--ranging from 838 to **1753** mm since 1962. Ninety per cent of this total annual precipitation occurs between the months of October and April. The frequent occurrence of summer coastal fog makes a small but unspecified contribution to the total precipitation in the form of fogdrip. Snowfall is a rare event at these elevations in this region.

While the Caspar Creek study site has been included in the region known as the rain-dominated Pacific Northwest, its climate is not entirely typical of the overall region which encompasses Northern California, Oregon, Washington, and British Columbia. This experimental watershed lies at the southern border of the region and is only about 5 km from the Pacific Ocean. Because of the lower latitude, proximity to the ocean, and lower elevations of the Caspar Creek site, the temperature regime here is warmer and less variable, and precipitation is less than the norm for the overall region.

Forest vegetation in this coastal region is the product of favorable climatic and soil conditions. The area supports fairly dense stands (averaging 700 m³ ha⁻¹) of second-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), coast redwood (*Sequoia sempervirens* (D. Don) Endl.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.). There are also some minor hardwoods, including tanoak (*Lithocarpus densiflorus* (Hook. and Am.) Rohn) and red alder (*Alnus rubra* Bong.), and some Bishop pine (*Pinus muricata* D. Don) scattering of old-growth redwoods remains within the Caspar Creek watershed.

The understory vegetation includes brush species such as evergreen huckleberry (*Vaccinium ovatum* Pursh), Pacific rhododendron

(*Rhododendron macrophyllum* D. Don), and sword fern (*Polystichum munitum* (Kaulf.) Presl.).

Historically, the most significant land management activity on the North Fork watershed occurred in the late 1800's when most of the original old-growth forest was removed by clearcut operations. Following the removal of timber, the watershed was burned. During World War II some minor pole and pile cutting was done, but since the original logging of nearly a century ago, human-induced disturbances within the North Fork drainage have been inconsequential.

Field installation

In this region, the discharge ends of soil pipes are commonly situated at the headwalls or sidewalls of gullies or sinkholes. These pipe outlets do not enter the gullies or sinkholes at any consistent level or position in the soil profile, but occur from near the soil surface to a depth of about 2 m. Pipe diameters range from 1 to 100 cm. Upslope from a gully headwall, the swale frequently leads to several sinkholes which are interconnected by pipes.

During winter 1986, two nearby swales exhibiting similar pseudokarst features were instrumented to study pipeflow. The contributing drainage area of swale M1 is 1.4 ha (Fig. 2(a)) and swale K1 is 0.9 ha (Fig. 2(c)). Soil pipes were exposed by trenching and enlarging existing gully features. Flow from individual pipes, overland flow, and flow through colluvial wedges was captured by driving metal flashing into the trench face and then routing the water into upright PVC containers (15 cm in diameter by 100 cm tall) (Fig. 2(b) and (d)). Drainage holes were drilled in the side of each container and a laboratory calibration was established between stage and discharge. At 10-min intervals, pressure transducers, placed in each of four containers, are interrogated by a 4-channel digital data logger, and data representing stage are written onto an EPROM chip.

At each swale, a large pipe, having a diameter from 15 to 45 cm, and 3 small pipes, having diameters from 2 to 8 cm, were instrumented. The large pipes generated storm peak discharges up to 8.5 l s^{-1} . The hydrograph response was similar to that of adjacent surface channels, in that baseflow was maintained between storm events. The small pipes generated storm peak discharges up to 0.3 l s^{-1} , with flow occurring only during peak periods of storm events. The large pipes were lower in the soil profile (1 to 2 m deep) than the small pipes (0.5 to 1 m deep).

Rainfall is measured at 5 locations within the 508-ha North Fork Caspar Creek watershed using tipping bucket raingages. These raingages have a 1-mm resolution and are interrogated at 5-min intervals. One raingage is located on the ridge near the headwater of swale M1. Streamflow and suspended sediment discharge is measured continuously at 12 stations within the North Fork watershed. One station (K) is about 5 m upstream from the mouth of swale K1, and another station (M) is about 500 m downstream from swale M1.

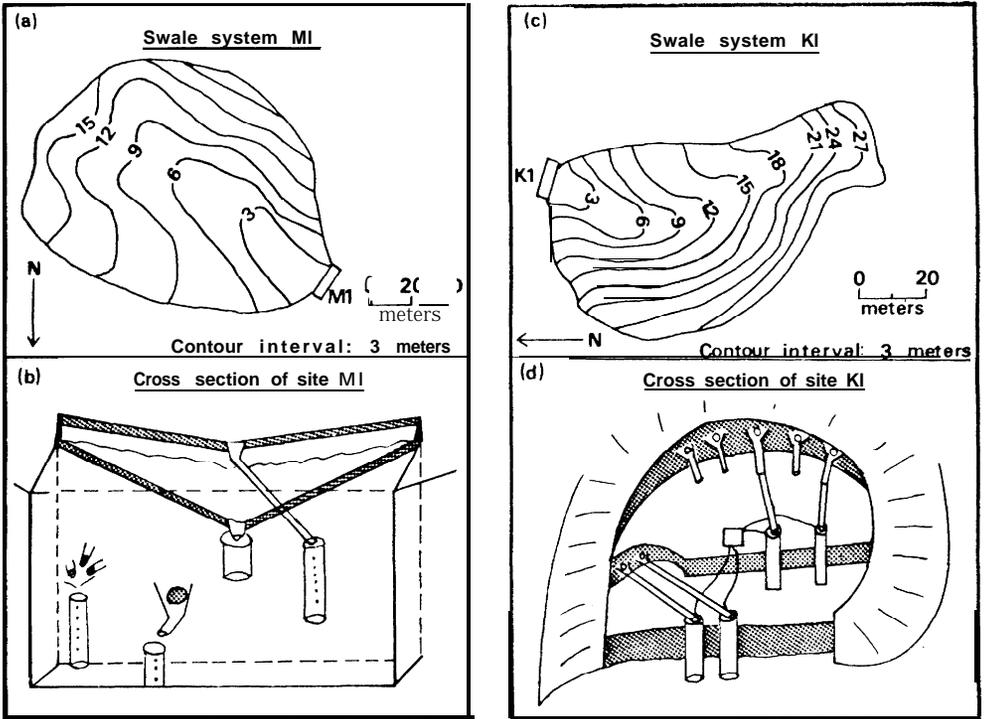


FIG.2 Topography of swale systems (a) M1 and (c) K1, and cross sections of piping sites (b) M1 and (d) K1.

RAINFALL AND PIPEFLOW RELATIONSHIP

Istock & Boersma (1986) studied surface runoff in coastal Oregon drainages of similar size to those in our study. They found antecedent precipitation before the storm to be a more important predictor of runoff processes than either rainfall magnitude or intensity in climates, such as ours, where low-intensity rainfall predominates. While they were not studying subsurface flow processes, their research demonstrated that soil moisture conditions prior to the storm are a dominant influence on flow paths taken by storm rainfall in this setting. Our analysis was directed toward clarifying this relationship.

The antecedent precipitation index (API) is commonly used to model the residual effect of previous precipitation on current soil moisture or runoff. For our study, the API at any time (i) was calculated by:

$$API_i = API_{i-1} \cdot c^{\Delta t} + P_i$$

where c is the decay constant characteristic of the particular recession, Δt is the time interval, and P_i is the precipitation that occurred during the i th interval of duration Δt . By inspection, a c -value of 0.7 was found to provide the best average approximation of pipeflow hydrograph recession.

Pipe discharge at Caspar Creek is predominantly a quickflow process, with some amount of soil wetting being required to initiate a pipeflow response. Once this response is achieved, additional rainfall input is rapidly reflected in pipeflow hydrographs. Seven storm events occurred between January 1986 and January 1987. During each storm, time and discharge were measured for (a) start of storm, (b) peak, (c) trough, and (d) end of storm. Some of the storms produced multiple peaks and troughs. The pipes were grouped into two classes--large discharge pipes (M106 and K102) and small discharge pipes (M190, K105, and K107).

The coefficient of determination, r^2 , between each hydrograph component, Y, and the API variable, X, was maximized by calculating a series of regressions (Ziemer, 1984) with various values of the time interval, Δt , for each discharge class (Table 1). The values for Δt that were tested ranged from 0.04 to 0.5 d. The smaller the value of Δt , the greater the responsiveness of the index to short-term rainfall intensities (Fig. 3). In addition, each regression series was repeated using one of several lag times. Lag time is the time difference between the hydrograph component and the associated API value, and was used to determine if there was a delay in the time of precipitation input and the hydrograph response. The lag times ranged from 0 to 0.5 d. For the 7 storms analyzed, using a non-zero lag time did not improve the performance of the regression model.

Start of storm

The regressions between the start of storm discharge and the API variable were only significant for the class of small pipes

TABLE 1 Time interval (Δt) which produced the regression having the maximum coefficient of determination (r^2) between the discharge (Y) for each hydrograph component and the API variable (X) for sample size (n)

| Hydrograph component | Large pipes | | | Small pipes | | |
|----------------------|-------------|----------------|-------|-------------|----------------|-------|
| | n | Δt (d) | r^2 | n | Δt (d) | r^2 |
| Start | 12 | n.s. | 0.21 | 23 | 0.50 | 0.35* |
| Peak | 19 | 0.25 | 0.66* | 33 | 0.50 | 0.60* |
| Trough | 15 | 0.50 | 0.61* | 13 | 0.04 | 0.60* |
| End | 11 | n.s. | 0.09 | 22 | n.s. | 0.02 |

* Regression significant at the 1% level.
n.s. Regression not significant.

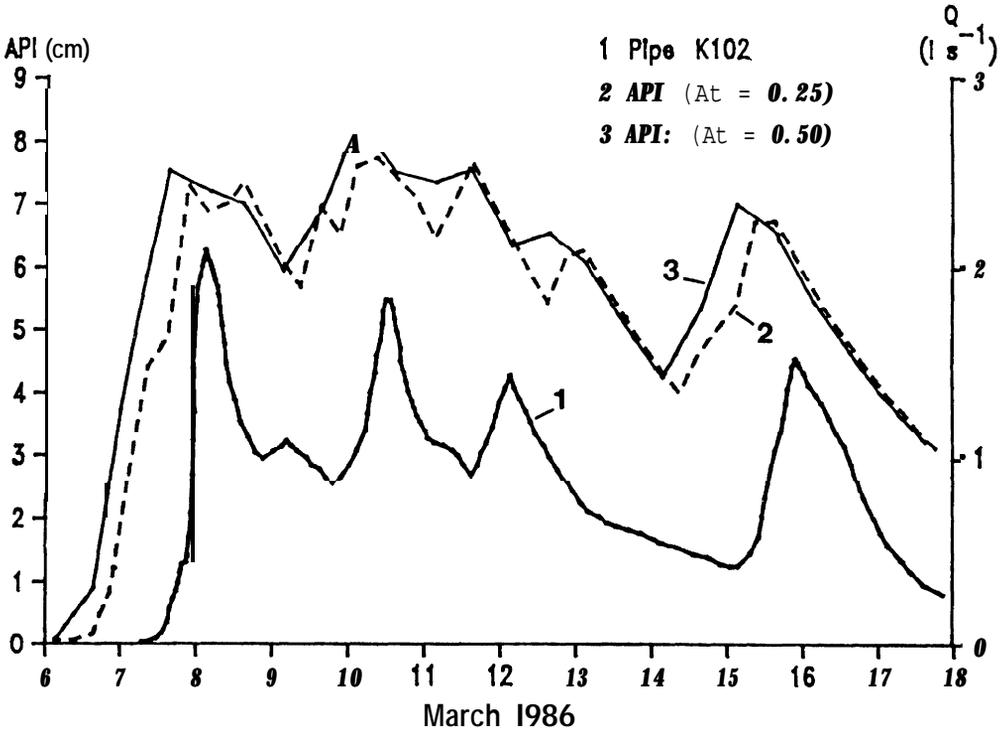


FIG.3 Discharge (Q) from large pipe K102 and API using two values for Δt during one storm.

(Table 1). The small discharge pipes are ephemeral and require some initial rainfall before they begin to flow. A similar observation was made by Tsukamoto *et al.* (1982). They reported that pipeflow did not begin until groundwater saturation reached the pipe level.

In contrast, response of the large discharge pipes is more complicated at the beginning of the storm. The results imply that there was a component of rapid contribution from an anastomosing network upslope, as well as a component of long-term delivery and drainage of the phreatophytic surface prior to the onset of rainfall. Our choice of t and c values was directed to evaluating short-term trends within storm periods, and may obscure the relationships governing the initiation of storm response in this class of pipes.

Jones & Crane (1984) studied piping processes in a humid upland basin in mid-Wales. The perennial and ephemeral pipes they measured produced greater discharges than those that we studied, but the hydrographs were similar in shape. They found that prestorm flow levels for the perennial pipes were correlated with total rainfall in the preceding 7 days. They also noted that for the ephemeral pipes, short-term antecedent conditions were more significant than longer-term conditions. Jones & Crane calculated antecedent conditions as an accumulation of precipitation over specified periods. They did not utilize a decay factor in their antecedent calculations.

Storm peaks and troughs

Jones & Crane (1984) reported that peak discharges in perennial pipes were correlated with flow levels prior to the storm and to total storm rainfall. For ephemeral pipes, peak discharges were controlled by rainfall intensities occurring before the peak,

Wilson & Smart (1984) looked at pipeflow in another catchment in Wales. They noted a fairly linear correlation between peak discharge and total storm rainfall when high soil moisture conditions preceded rainfall input. Pipeflow response time was observed to decrease with increasing soil moisture.

For both the large and small pipes at Caspar Creek, the API variable produced significant regressions for both the storm peak discharge and within-storm trough hydrograph components (Fig. 4). For peak discharge from large pipes, the time interval (Δt) which yielded the greatest r was 0.25 d, whereas, for the small pipes, the "best" value for Δt was 0.50 d (Table 1). This implies that once the storm is in progress and the hydrograph is rising, flow from the large pipes is more responsive to short-term rainfall intensities than is that from the small pipes. This observation is different than that reported by Wilson & Smart (1984).

When the falling limb of the hydrograph is interrupted by the rising limb, a trough is formed. Discharge at this point can be considered a special case of the start of storm hydrograph component, in which the soil is still draining from the previous storm and baseflow has not yet been attained. The small, ephemeral pipes are still flowing. Under these conditions, the "best" Δt value for predicting trough discharge for the large pipes was 0.50 d, and for the small pipes was 0.04 d--indicating that the small pipes were responding to shorter-duration rainfall intensities than were the large pipes.

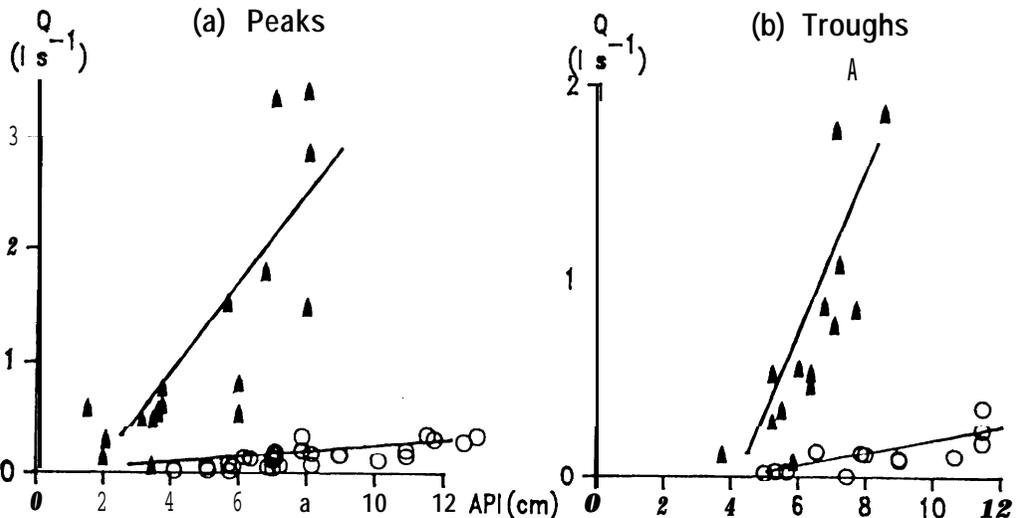


FIG.4 Relationship between discharge (Q) and API for large (▲) and small (○) discharge pipes at sites M1 and K1 for (a) storm peaks and (b) troughs.

End of storm

Wilson & Smart (1984) found a relationship between persistence of pipe discharge after the rainfall event and total storm rainfall. For our pipes at Caspar Creek, we could find no significant relationship between the API variable and end-of-storm discharge.

CONCLUSION

Nearly all of the discharge that we observed at our sites came from pipeflow. There was very little seepage from the excavation face, even during storm periods. This is similar to observations by Tsukamoto et al. (1982). They reported that pipeflow was responsible for 95% of the outflow from a small granitic headwater catchment in Japan. Seepage through the soil matrix at their location was negligible. In another setting, Jones & Crane (1984) found that pipeflow accounted for 46% of the streamflow generated from their study area.

Climate and geology vary for the limited number of studies of pipeflow hydrology conducted to date. These studies firmly establish the concept that macropore and piping networks are locally significant mechanisms for routing water and sediment from steep upland watersheds.

ACKNOWLEDGEMENTS This work was partially supported by McIntire-Stennis Grant no. CAL200090 and was conducted in cooperation with the California Department of Forestry and Fire Protection.

REFERENCES

- California Department of Forestry (1989) Soil-vegetation survey, Jackson State Forest, Mendocino County. The Resources Agency, State of California, Sacramento.
- Dredge, L.A. & Thorn, B.G. (1976) Development of a gully-flow near Sept-Iles, Quebec. Can. J. Earth Sci. 13 (8), 1145-1151.
- Durgin, P. (1984) Subsurface drainage erodes forested granitic terrane. Physical Geography 4 (1), 24-39.
- Goldsmith, P.R. & Smith, E.H. (1985) Tunnelling soils in South Auckland, New Zealand. Engineering Geology 22 (1), 1-11.
- Halladay, W.H. (1960) Pseudokarst in the United States. Nat. Speleolog. Soc. Bull. 22, pt. 2, 109-113.
- Higgins, C.G. (1984) Piping and sapping: development of landforms by groundwater outflow. In: Groundwater as a Geomorphic Agent (ed. by R.G.LaFleur), 18-58. Allen & Unwin, Troy, NY.
- Istok, J.D. & Boersma, L. (1986) Effect of antecedent rainfall on runoff during low-intensity rainfall. J. Hydrology 88, 329-342.
- Jones, J.A.A. & Crane, F.G. (1984) Pipeflow and pipe erosion in the Maesnant experimental catchment. In: Catchment Experiments in Fluvial Geomorphology (ed. by T.P.Burt & D.E.Walling), 55-85. Geo Books, Exeter.

- Kirkby, M.J. & Chorley, R.J. (1967) Throughflow, overland flow, and erosion. Int. Assoc Scientific Hydrol. Bull. 12, 5-21.
- Parker, G.G., Shown, L.M. & Ratzlaff, K.W. (1964) Officer's Cave, a pseudokarst feature in altered tuff and volcanic ash of the John Day formation in eastern Oregon, Geol. Soc. Am. Bull. 75, 393-402.
- Tsukamoto, Y., Ohta, T. & Noguchi, H. (1982) Hydrological and geomorphological studies of debris slides on forested hillslopes in Japan. In: Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proc. Exeter Symp., July 1982), 89-98. IAHS Publ. no. 182.
- Wilson, C.M. & Smart, P.L. (1984) Pipes and pipe flow process in an upland catchment, Wales. Catena 11 (2/3), 145-158.
- Ziemer, R.R. (1984) Response of progressive hillslope deformation to precipitation. In: Symposium on Effects of Forest Land Use on Erosion and Slope Stability (ed. by C.L. O'Loughlin & A.J. Pearce), 91-98. East-West Center, Honolulu.