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A CASE STUDY OF SHALLOW FLOW PATHS IN A STEEP ZERO-ORDER BASIN[1]

J. J. McDonnell, Ian F. Owens, and M. K. Stewart[1]

ABSTRACT: Soil water potentials, slope throughflow, runoff chemistry, and isotopic composition were monitored in a 97 m^2 zero-order basin within the Maimai 8 watershed on the South Island of New Zealand, for a natural rain storm and two artificial water applications. Contrary to results previously reported for other portions of the Maimai catchment, much of the runoff occurred as a shallow subsurface organic layer flow. For the 47 mm natural rain event, pre-storm soil matric potential ranged from -60 to -150 cm H_2O. No saturation was produced within the profile, and the majority of storm runoff emanated from flow within the organic horizon perched on the mineral soil surface. Hillslope applications corroborated this interpretation by showing >90 percent new water flushing with negligible mineral soil moisture response. Although the mechanisms cited in the text are not representative of the entire catchment, the study demonstrates: (1) the value of a combined physical-chemical-isotopic approach in quantifying slope processes, and (2) the heterogeneous nature and diversity of slope runoff pathways in a relatively homogeneous catchment.
(KEY TERMS: forest hydrology; infiltration and soil moisture; water quality; instrumentation; watershed management/wildland hydrology.)

INTRODUCTION

Since the early work of Horton (1933), hydrologists have examined the rates and pathways of runoff production in an attempt to model water transfer through catchments of various sizes. For flood routing, relatively simple assumptions regarding runoff pathways have been adequate for successful modeling. However, as water quality considerations are incorporated into many distributed models of saturated and unsaturated flow in hillslope soils (e.g., Khan and Ormsbee, 1989), more detailed understanding of water movement pathways, residence times, and water origin is required for successful model implementation. This is particularly true for acid rain and contaminant transport investigations, in which details of not only the magnitude of water flux, but also its complete movement history within the catchment, are important.

The key to solving the above and other related problems is through fundamental research into the rainfall-runoff process. At present, further progress in understanding processes of storm runoff generation in humid headwater catchments is hampered by discrepancies often found between the different approaches to quantifying water movement. Results from chemical and natural isotope separations of streamwater into old (pre-event) and new (event) water sources often appear to contradict results from hydrometric studies of pathways of water movement on hillslopes. Church *et al.* (1990), note that geochemical research has focused generally on understanding the basic processes that occur in soils and rocks, and much less concerning water movement through catchments and its effects on the temporal variation in the chemical composition of surface waters. Although hillslope hydrologists have understood that flow paths can be better elucidated if the geochemical and isotopic history of waters is known, integrated studies of this nature have been lacking. Furthermore, Rodhe (1987) and others note that there is a gap between detailed investigations of single hillslopes (Anderson and Burt, 1978) and the basin input-output studies in which isotopes are used as tracers (Sklash and Farvolden, 1979), and few studies have been reported where the two types of investigation have been performed in the same basin.

This paper presents a case study of shallow flow generation in a steep catchment. The study forms part of a larger investigation of subsurface runoff

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[2]Respectively, Assistant Professor, Watershed Science Unit, Department of Forest Resources, Utah State University, Logan, Utah 84322-5215; Senior Lecturer, Department of Geography, University of Canterbury, Christchurch, New Zealand; and Senior Scientist, Institute of Nuclear Sciences, Department of Scientific and Industrial Research, Lower Hutt, New Zealand.

mechanisms and isotope hydrology, reported by McDonnell (1990), McDonnell *et al.* (1990, 1991), and Stewart and McDonnell (1991). Although the mechanisms cited in the text are not representative of the entire catchment, the study demonstrates: (1) the value of a combined physical-chemical-isotopic approach in quantifying slope processes, and (2) the heterogeneous nature and diversity of slope runoff pathways in a relatively homogeneous catchment.

SITE DESCRIPTION AND METHODS

A 97 m^2 zero-order basin was monitored within the 3.8 ha Maimai 8 catchment, located on the West Coast of New Zealand. The catchment and subbasin have been described in detail by Pearce *et al.* (1986), and McDonnell (1990). Briefly, the site is humid (2700 mm rain annually), with 8 year old Pinus Radiata, and maintains steep (40°), highly incised slopes. Flow out of the zero-order basin was measured using a 3.3 m long cement trough installed in a trench dug at the soil-bedrock interface (Pit A in Figure 1). Flow was monitored continuously using a mini 10:1 v-notch weir mounted directly on to a 210 L storage drum with recording pressure sensor.

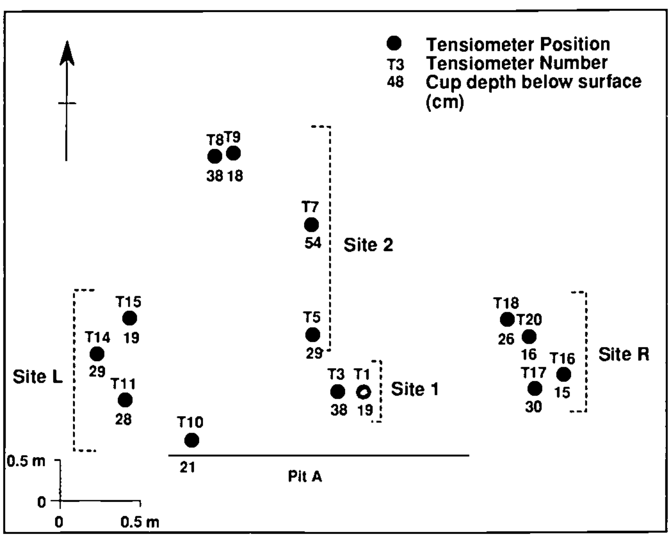

Figure 1. Zero-Order Basin Tensiometric Grid Upslope From Subsurface Flow Pit (Pit A).

Soil depth in the basin averaged 500 mm. The OH horizon (0-180 mm) consisted of a dark brown fibrous humus with many small roots. The B_2 horizon (180-500 mm) consisted of a light grey, strongly gleyed silty clay, with many 5-15 mm diameter clasts with stained exterior surfaces. Bulk densities averaged 1.5 (s.d. ± 0.2) g cm^{-3}, with porosities on the order of 45 (s.d. ± 8.3) percent. Webster (1977) reported average infiltration capacities of the OH horizon and average saturated hydraulic conductivity of the B_2 horizon of 6100 and 250 mm hr^{-1}, respectively.

A Scanivalve recording tensiometer system (described by McDonnell, 1990) was connected to a Campbell 21X logger and used to continuously monitor soil matric and pressure potentials (ψ). Cup depths, numbers, and positions are shown in Figure 1. The weir pressure sensor and a tipping bucket raingage were also connected to the logger for time-synchronous measurements. An automatic liquid sampler was attached to the weir drum for sampling surface and subsurface stormflow at regular intervals. Two natural rain events were monitored. Artificial hillslope applications were then performed, where water was applied to the soil surface through a 1.5 m wide trough, with holes drilled at 100 mm intervals along the base. Application rates averaged 3 L min^{-1}, with total application volume of 30 L. The trough was positioned 1 m upslope from the trench face. Rates of application were consistent with the range of subsurface flow discharges observed by Mosley (1979) under natural rain events (c. up to 5 L min^{-1} m of $contour^{-1}$). Outflow from the face was monitored by timing and filling varying combinations of 100, 250, and 1000 ml beakers for periods of 5-60 sec. Water samples were also collected at various times throughout tracer hydrograph for chloride and deuterium analysis.

RESULTS AND INTERPRETATION

Hydrometric Data

On November 26 and 27, 1987, 47 mm of rain fell on to the zero order basin in two separate bursts. Peak 10 min rainfall intensities were > 12 mm hr^{-1}, and would have temporarily exceeded mineral soil surface infiltration capacities in the basin, as demonstrated by McDonnell (1990). Antecedent precipitation indices (API_7 and API_{14}, representing 7 and 14 days) were defined by

$$API_x = \sum_{i=1}^{x} P_i / i$$

where P_i is the total gross precipitation on the ith day beforehand. API_7 and API_{14} were low, on the order of 1.5 and 4.1 mm, respectively.

The two rain bursts are treated as separate events. During the period 0000 to 2200 hours, November 26 (Figure 2), 22 mm of rainfall produced a peak discharge of about 800 ml min^{-1}. Peak ψ response at the site coincided with peak throughflow at 2000 hours, except for some tensiometer positions, where peak ψ preceded pit throughflow peak by approximately three hours (Figure 2D, E). Pre-storm ψ for most tensiometer positions was between –60 and –150 cm H_2O. The highest magnitude ψ attained during rainfall was –28 cm H_2O, and no saturation was detected in any portion of the profile. Near the 3.3 m trenched face at Site 1 (Figure 2C), equilibrium conditions were maintained prior to the event. T1 (19 cm) responded immediately to the rain input at 0300 hour. Matric potential shifted from –60 cm H_2O to a peak value of –35 cm H_2O over the following nine hours, and then remained constant for the duration of the event. T3 (38 cm) matric potential response to storm rainfall lagged T1 by c.11 hours, but response was more rapid (–90 to –45 cm H_2O in seven hours) and peaked at the same time as pit throughflow. Matric potential response to rainfall from other tensiometer locations (Figure 2) is similar to Site 1. Sites 2, L and R (locations shown in Figure 1) maintained higher magnitude pre-storm ψ, but showed similar response magnitudes and timing to Site 1.

Approximately five hours after the November 26 rain burst, another 18 mm of rain fell on the basin, named the November 27 event (Figure 3). Peak discharge was 6000 ml min^{-1}, and again peak 10 min rainfall intensities exceeded 12 mm hr^{-1}. No saturation was observed in any portion of the soil profile and ψ response to rain input for each tensiometer group was minimal. Pre-storm ψ was equivalent to November 26 post-storm ψ, and no significant soil profile drainage occurred between events. At Site 1, ψ remained nearly constant for the complete November 27 event and did not significantly deflect from pre-storm values. Site 2 tensiometers showed some decrease in ψ magnitude at 0900 hour, which coincided with the end of rain input. Sites L and R registered little response.

Both tensiometric and throughflow response for the November 26 and 27 events are consistent with the qualitative interpretations of Mosley (1979, p. 802), whereby "a large portion [of runoff] runs downslope above the surface of the B horizon. A distinct saturated zone 10-20 mm deep in the base or the organic layer was frequently observed during storm conditions, and it is inferred that water moves downslope through this saturated highly porous layer in a manner intermediate between free surface flow and flow

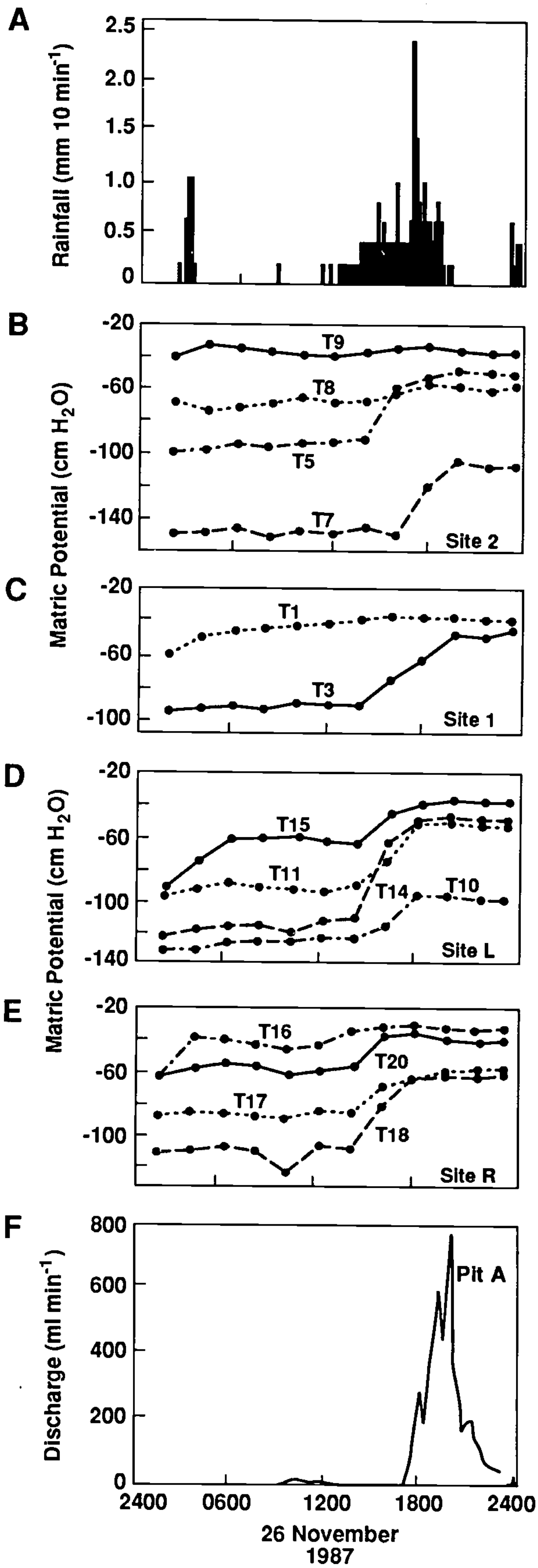

Figure 2. Hydrometric Response for Selected Tensiometer Sites, November 26, 1987.

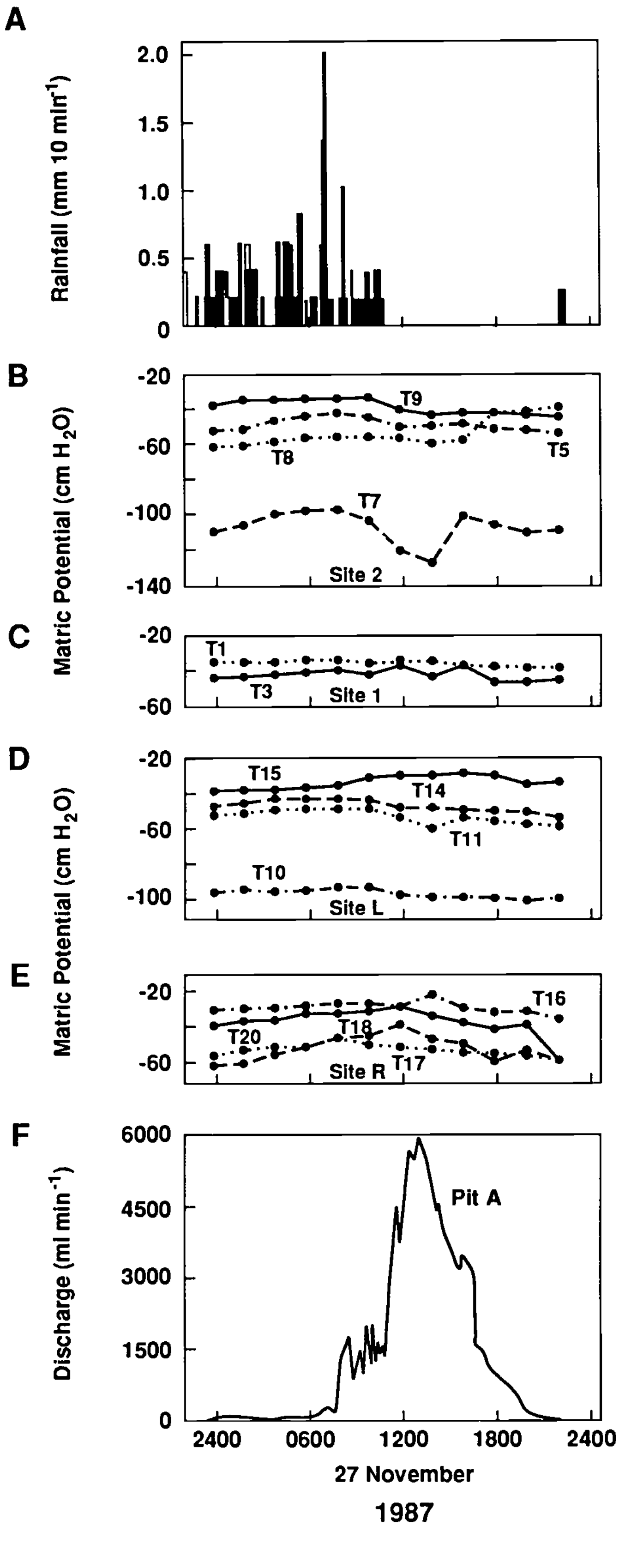

Figure 3. Hydrometric Response for Selected Tensiometer Sites, November 27, 1987.

through a porous medium." This interpretation is verified in the present study by the fact that considerable volumes of throughflow were produced, without any saturation of mineral soil or significant change in soil ψ. The distinct saturated zone described by Mosley (1979) was identified in this study as organic layer saturated flow, perched on the mineral soil surface.

Throughflow in the zero order basin is formed by saturated flow in the litter and OH horizons; whereby water moves through the OH horizon perched on a permeability contrast between the OH and B_2 horizons. This is somewhat different to Mosley's conceptualization of flow being somewhere between "free surface flow and porous medium flow." In any case, rain intensities for the November 27 storm temporarily exceeded mineral soil infiltration capacities, and forced water to flow over the B2 surface to produce the measured throughflow response. No bypass flow (as described by McDonnell, 1990) was detected.

Chemical-Isotopic Data

In order to corroborate and shed further light on the hydrometric analyses, chemical and isotopic tracing was conducted in the zero-order basin during the November 26 and 27 events. Results for the larger M8 catchment, into which the zero-order basin drains, are described in detail in McDonnell *et al.* (1991). Detailed chemical and isotope data are shown in Figure 4. Basin outflow showed a large δD deflection away from pre-storm soil water (c. –37 percent) and toward rain δD, with peak new water outputs [computed by methods described in McDonnell *et al.* (1990)] of 25 percent. Outflow water showed large increases in Cl concentration and EC, indicating increased total solute concentration. Although both of these shifts were away from rain chemistry values, they may indicate the flushing of high Cl and solute-rich water that had been enriched during evaporative conditions preceding the event.

Although rain amounts and intensities for the storms were similar, the second rain burst produced 7.5 times more flow at the basin outlet. The tensiometer data, described earlier, seem to indicate that during the November 26 storm, a large portion of the rain input infiltrated into the soil matrix, with possibly some mineral soil surface flow during the most intense short burst at 1800 hour. As a result, only about 90 L of throughflow was produced, with no detectable new water. Presumably, the first rain input would also have filled the unsatisfied water storage capacity in the organic layer (5-15 mm from data in Webster, 1977). Throughflow rates and volumes indicate that the majority of the second burst of rainfall did not enter the soil matrix, but rapidly flowed through the organic horizon, "perched" on the permeability contrast at the mineral soil surface. This is corroborated by the isotopic tracing application experiment (described in the next section), where new water contributions reached approximately 90 percent at peak flow (Figure 5). Without the unsatisfied moisture deficits in both the organic and mineral soil to fill, runoff production was much higher (> 1000 L at the trench face).

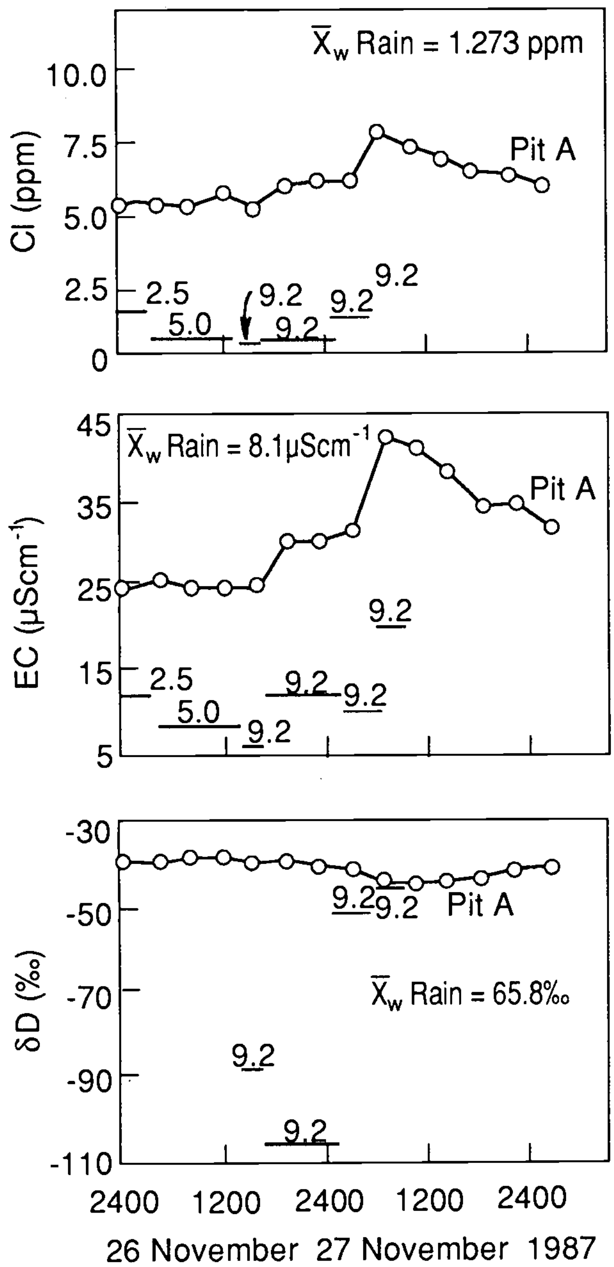

Figure 4. Deuterium, Chloride, and Electrical Conductivity Plots for Zero-Order Basin Outflow (Pit A) and Rainfall.

Hillslope Tracer Applications

Two hillslope applications were performed to validate experimental results described previously. In the first application (Figure 5), 30 L of water was applied to the soil surface 1 m upslope from the outflow trench. Antecedent wetness conditions (API_7 and API_{14}) were high compared to the November 26 event, and were 7.9 and 11.7 mm, respectively. No rain had fallen within three days of application. Water first appeared at the trench face at 2.5 min (Figure 5A). The outflow hydrograph responded very rapidly, with peak outflow (3400 ml min^{-1}) at 6-8 min after initial application. Audible rushing of water through the organic layer and over the mineral soil was observed, particularly within the first 10 min of hydrograph response. Approximately 68 percent of the applied water was recovered at the pit face within 50 min, at which time flow rate had dropped to only trace amounts.

Cl variations through the simulated event showed considerable flushing of new (applied) water. Old (stored) soil water seepage from the face was 7.30 ppm. The first water sample (4 min) showed considerable new water flushing (new water = 3.24 ppm), with Cl concentrations dropping to 4.02 ppm. Cl concentration reached its lowest value at 6 min (3.79 ppm), and then rose gradually for the next 50 min to a value of 4.49 ppm (Figure 5B). δD values reflect the Cl changes, but show some increase in old water discharge at c.20 min and then back to new water values (Figure 5C). δD interpretation is limited in this case because the applied new water δD value (–35.3 ‰) was only 1.3 ‰ away from the pre-event flow value (–36.6 ‰). Since the analytical precision is ± 1 ‰, δD trends in this case must be treated with caution. For this reason also, hydrograph separation was not performed based on δD values.

Hydrograph separation using the Cl values in the mass balance is shown in Figure 5D. Very large new water volumes are evident in the separation, particularly during the peak hydrograph response. This is again indicative of rapid flushing of new water as described above. Old water percentages are plotted in Figure 5E and show that, using the Cl separation, old water moved from a minimum of 10 percent at peak flow, steadily upward to a peak value of approximately 35 percent as the soil slowly drained after the application. Old water percentages based on the δD mass balance are also shown in Figure 5E, and reenforce the problems noted earlier regarding its relevance for this experiment. Old water percentages were unrealistic in many cases (i.e., > 100 percent and < 0 percent), as noted in the plot.

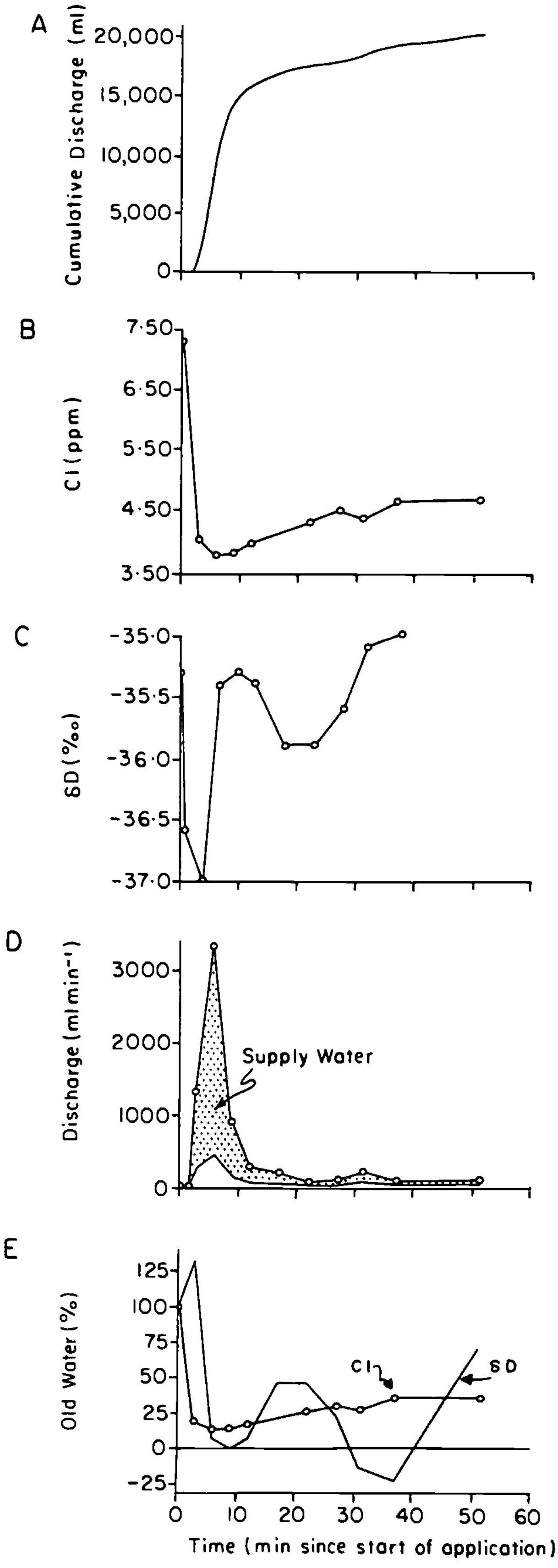

Figure 5. Slope Application Results for the First 30 L Application 1m Upslope From the Trench Face. Hydrograph separation (5D) using Cl as tracer.

A second application is presented as an example of tensiometric response to an identical 30L water application. Matric potential response was negligible (Figure 6), and reinforces the isotopic interpretation of rapid flushing over the mineral soil surface as a shallow subsurface or pseudo-overland flow, without contacting the soil matrix. T1 and T13 showed no response within 50 min of application (Figure 6B) or even 200 min after application (Figure 6A). T2 and T3 showed a very slow ψ shift of c. 10 cm H_2O over 50 min (Figure 6A), and then peaked roughly 100 min after application. This peak represents slow vertical drainage through the profile, which would presumably continue propagating downward to the T1 and T13 tensiometer sites, sometime after 200 min.

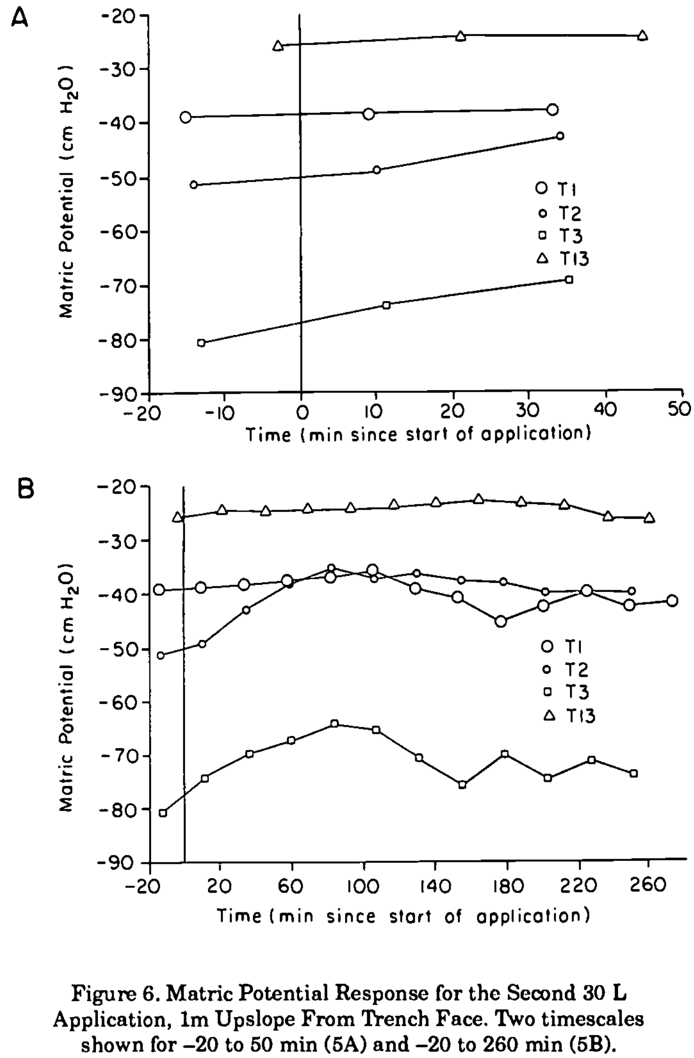

Figure 6. Matric Potential Response for the Second 30 L Application, 1m Upslope From Trench Face. Two timescales shown for –20 to 50 min (5A) and –20 to 260 min (5B).

CONCLUSION

Soil water potentials, slope throughflow, runoff chemistry, and isotopic composition were monitored in a 97 m^2 zero-order basin within the Maimai 8 watershed for a natural rain storm and two artificial water applications. Although pre-storm soil matric potentials were relatively low (–60 to –150 cm H_2O) for the 47 mm natural rain event, no saturation was produced within the profile, and the majority of storm runoff emanated from flow within the organic horizon, perched on the mineral soil surface. 30 L line source water applications corroborated this interpretation by showing > 90 percent new water flushing with negligible mineral soil moisture response.

Although the mechanisms cited in the text are not representative of the entire catchment, the study demonstrates that small portions of drainage basins may behave differently to conventional notions of runoff production (McDonnell, 1990). Although unable to document all varieties of mechanisms, hydrologists must recognize the very large range of possibilities of slope processes and incorporate some degree of this heterogeneity into their models. In hydrogeochemical investigations, these small anomalies may have a large control on slope water chemistry and stream response. Cumulative study on a limited set of highly instrumented basins is probably the most fruitful approach in process hydrology. However, some process extremes must also be addressed. This study also demonstrates the value of a combined physical-chemical-isotopic approach in quantifying slope processes.

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