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Subsurface Flow in a Shallow Soil Canadian Shield Watershed

Adrian V. E. Renzetti, Colin H. Taylor and James M. Buttle

Trent University, Peterborough
Ontario, Canada K9J 7B8

Past studies in Canadian Shield headwater catchments have identified the importance of subsurface flow mechanisms in generating storm runoff. Recent work in the Muskoka-Haliburton region of south-central Ontario has suggested that subsurface flow within hillslopes with shallow soils occurs primarily along impermeable bedrock surfaces. Two trenches were dug on the side slope of a small headwater catchment and instrumented to measure flows at different levels in the soil. Results show that flow over the bedrock surface constitutes the largest component of hillslope discharge during fall rain storms. Peak discharge and recession rates for bedrock surface flow hydrographs were synchronous with channel discharge. Calculations show that this component of hillslope flow could account for the majority of peak discharge during storm events.

Introduction

A variety of approaches have been used to investigate runoff processes in small watersheds. These include hydrometric measurements (*e.g.* Dunne *et.al.* 1975) and hydrograph separation techniques using natural isotopes (*e.g.* Sklash *et al.* 1986) and chemical species (*e.g.* Kennedy *et al.* 1986). Many studies attempt to explain the chemistry of watershed outflow (particularly under acid precipitation conditions) in terms of flow pathways and residence times of water in various storage zones in the catchment (*e.g.* Peters and Driscoll 1987, Swistock *et al.* 1989). In particular, the relative mix of event water (assumed to have followed a predominantly surface or near-surface pathway) and older groundwater appears to be the major factor affecting streamwater chemistry. This has led to the development of two-reservoir mixing models (*e.g.* Bobba and Lam 1986, Christophersen *et al.* 1982). Previous work in the Muskoka-Haliburton region of Ontario (Wels *et al.* 1991) and the Adirondacks (Lawrence *et al.* 1988) suggests that source areas for runoff vary spatially and temporally. Further, subsurface flow processes are variable and complex. Some recent investigations (*e.g.* Sklash *et al.* 1986) indicate that conventional Darcian flow is not able to explain subsurface flow volumes and response times and suggest that some sort of macropore flow system must be operating. Many types have been proposed (*e.g.* Mosley 1979, Roberge and Plamondon 1987) but few studies have explicitly documented the operation of the process. The mechanism is important not only because it allows for the relatively rapid delivery of pre-event water to stream channels, but also for the delivery of event water via subsurface pathways. Macropore flow itself is not yet well understood, nor is the way in which event and pre-event water mix in the soil matrix and/or the macropores.

Previous work in the Muskoka-Haliburton region of south-central Ontario has identified subsurface flow as the dominant runoff process within the slopes of glacial till catchments. McDonnell and Taylor (1987) and Shibatani (1988) used a combination of surface saturation mapping (to identify surface runoff contributing zones) and shallow wells to infer that flow over the bedrock surface was the dominant process delivering stormwater to the stream channel from slopes with thin soil cover. Both studies showed that saturated layers develop at the bedrock surface, thickening towards the base of the slope. These findings were supported by Wels (1989) who used isotopic and chemical separation techniques to establish that most event and pre-event flow followed a subsurface route. All three investigations pointed to flow along the soil/bedrock interface as the most likely mechanism delivering water to stream channels. In none of these studies, however, was flow at the bedrock surface measured directly.

The purpose of this study was to investigate further the subsurface flow mechanisms operating within the Plastic 1 (PC-1) watershed in Muskoka-Haliburton using hydrometric techniques. The following hypotheses were tested:

1) During rain events the dominant flux of subsurface flow will be along the soil/bedrock interface.
2) This component of subsurface flow will be the main contributor to streamflow during rain events.

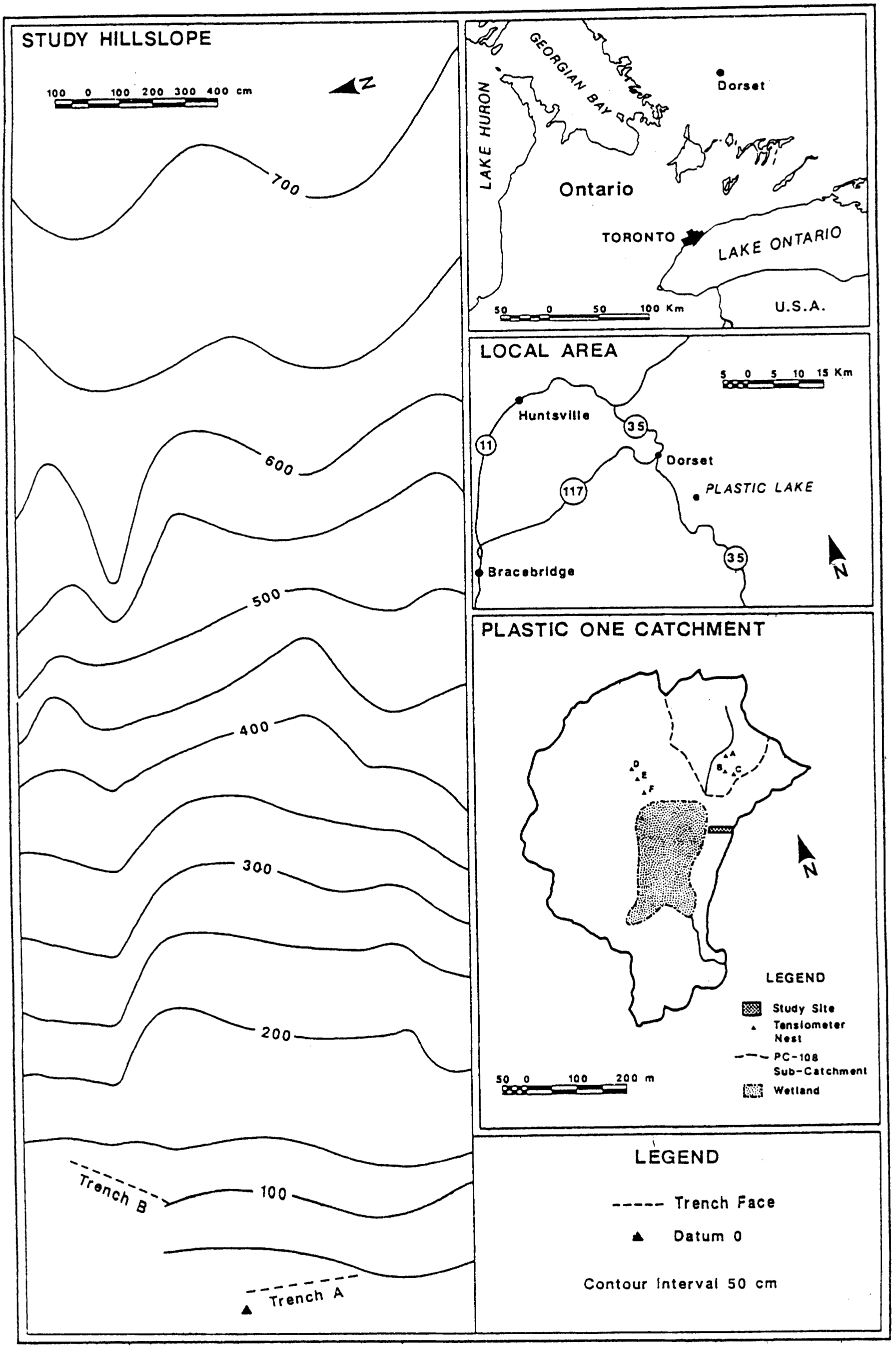

Fig. 1. Location of the PC-1 and PC-108 catchments, tensiometer nest locations, and topography of the study hillslope.

Study Site

Plastic Lake is located south of Dorset, Ontario (45°11'N, 78°50'W). The lake is fed by six, mainly ephemeral, headwater streams. The hillslope used for this study was located on the west slope of Plastic Lake catchment 1 (PC-1) as designated by the Ontario Ministry of Environment (M. O. E.) (Fig. 1). PC-1 has a drainage area of 23.35 ha. Annual average precipitation for the area is 971 mm, with 85 mm and 92 mm occurring mainly as rainfall during October and November, respectively (Environment Canada 1982, 30-year mean).

The east slope of PC-1 is underlain by Precambrian ortho-gneissic bedrock and has a thin till cover with some exposed rock ridges (Girard *et al.* 1985). Weakly developed orthic humo-ferric podzols (Lozano *et al.* 1987) have formed on the till mantle. These soils, along with orthic ferro-humic podzols, occupy almost 75 % of PC-1 (Lozano *et al.* 1987). Vegetation cover consists mainly of coniferous forest, with white pine, hemlock and cedar as the dominant species. Deciduous species are not as common and mainly consist of white birch, red oak and striped maple (Shibatani 1988).

Methods

Research was conducted on a hillslope on the east side of PC-1 (Fig. 1) that was considered representative of side slopes in the catchment. It had an average soil depth of 0.4 m, with a bedrock slope of 0.21 and length of approximately 37 m. Two trenches, 5 m from the base of the slope, were excavated in order to monitor subsurface flow from an upslope area of approximately 435 m^2. Trench A was 3.13 m in length, 0.5 m wide, 0.48 m deep and drained 340 m^2. Two soil horizons were present: an organic/Ae horizon (0.07 m) and a B horizon (0.41 m) extending down to the bedrock surface. Trench B was 3.15 m in length and 0.5 m wide, but only 0.1 m deep and drained an upslope area of 95 m^2. In this case bedrock was overlain by the organic layer only. In both trenches the bedrock surface was cleaned and a polyvinyl gutter was fixed in place with silicon caulking to divert flow over the surface to monitoring devices. In Trench A, two stainless steel trays, 24.5 cm in width, were inserted into the trench face to collect flow at two levels in the soil (Fig. 2). The first was at the base of the organic/Ae layer. This would capture any flow through or over the organic layer, although surface flow was unlikely because of the porous nature of the organic mat. The second tray was positioned within the B horizon, 0.12 m above the bedrock surface (Fig. 2). Although this gutter would not collect all of the B horizon flow, it was important to monitor it separately from the flow that was expected to occur through a saturated layer directly over the bedrock surface. In all cases, flow from the collectors was funnelled into ABS pipes and directed to recording devices. Flow from the bedrock surface in Trench A was passed into a 214 l drum equipped with a Leopold-Stevens water level recorder.

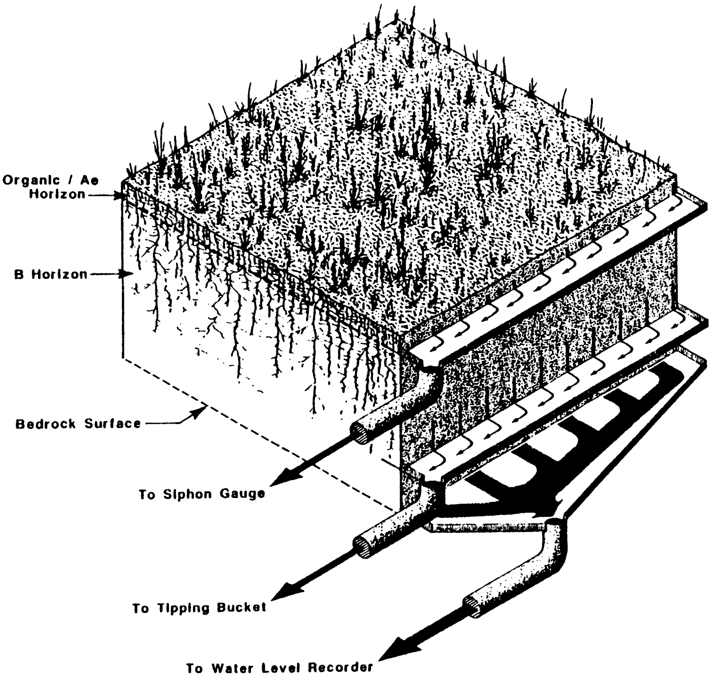

Fig. 2. Schematic representation of the drainage collection levels for Trench A.

Discharge was continually recorded to an accuracy of ± 2.4 %. Flows from the two soil levels in Trench A and from the soil surface in Trench B were monitored by positioning the end of the ABS pipes above recording raingauges, which were calibrated to provide a record of flow rates via a Campbell 21X datalogger. Signals were logged every 15 s and averaged over 15 minute periods.

Atkinson (1978) outlined two problems associated with the use of open faced pits to monitor lateral flows: the creation of unnatural saturated wedges upslope, and distortions to the natural flow net. We consider these effects as probably not too serious in this study, partly because a saturated layer does exist naturally at the bedrock surface, and partly because the soil is very thin, so there is little scope for changes in the pattern of hydraulic potential upslope of the trenches.

Data from six tensiometer nests, maintained by the M. O. E. and located within 125 m of the trench site, were used to infer antecedent soil moisture conditions (Fig. 1). Individual tensiometers were located at depth intervals of 0.15 m and extended from 0.15 m to 0.6 m beneath the soil surface. In order to relate hillslope response to catchment response, discharge data from PC-108 were used. PC-108 is a 3.45 ha sub-catchment of PC-1, and is gauged within 60 m of the trench site. Rainfall intensity was recorded at 10-minute intervals at a nearby M. O. E. meteorological station, using a Belfort weighing raingauge. Values were then integrated over periods of 1 h.

Bulk water samples were taken during three storm events from the trenches and analyzed for Ca, SiO_3, Mg, K, DOC, NH_4 and NO_3, in order to assist in the inference of runoff pathways or residence times. Chemical concentrations were determined as outlined in the Ontario Ministry of Environment (1981).

Results and Discussion

Six rain events were monitored during October and November, 1989. They were of varied duration and intensity and produced a range of hillslope responses. Rainfall characteristics for the six events are given in Table 1. Total rainfall represents 91 and 24% of normal October and November precipitation, respectively. If November rainfall is prorated over the whole month, it is seen that the amount received during the measurement period was not atypical. Based on independent rainfall measurements, it was found that beneath-canopy rainfall was 10% less than open area totals on average. The possibility thus exists that inputs to the hillslope used here are over-estimates of actual values.

Records of flow at the bedrock surface from Trench A were incomplete for several events due to equipment failure and overflow from the drum capturing subsurface discharge. However, missing data were estimated using regression relationships with the B horizon flow.

Soil Matric Potential

The six tensiometer nests showed similar general patterns throughout the study period (Fig. 3). Soils were driest during early October. Rainfall on October 10 and 15 resulted in the wettest conditions of the study period prior to the third rain event on October 20. Following this event no rain fell for eight days, allowing soils to dry considerably by the time of the largest rainfall input on October 31. Thus, a variety of antecedent moisture conditions existed over the one-month period.

In comparing the upslope changes in soil matric potential, similarities were observed between the two sites. The lower slope nests show somewhat opposite trends to the mid and upslope nests (Fig. 3). At these lower sites, saturation of the

Table 1 – Rainfall statistics for the six monitored storms.

Storm Event	Total Rainfall (mm)	Peak Intensity (mm h^{-1})
Storm 1, Oct. 10	14.2	2.8
Storm 2, Oct. 15	24.5	7.4
Storm 3, Oct. 20	13.2	3.3
Storm 4, Oct. 31	22.3	11.9
Storm 5, Nov. 2	6.7	1.1
Storm 6, Nov. 6	15.2	3.4

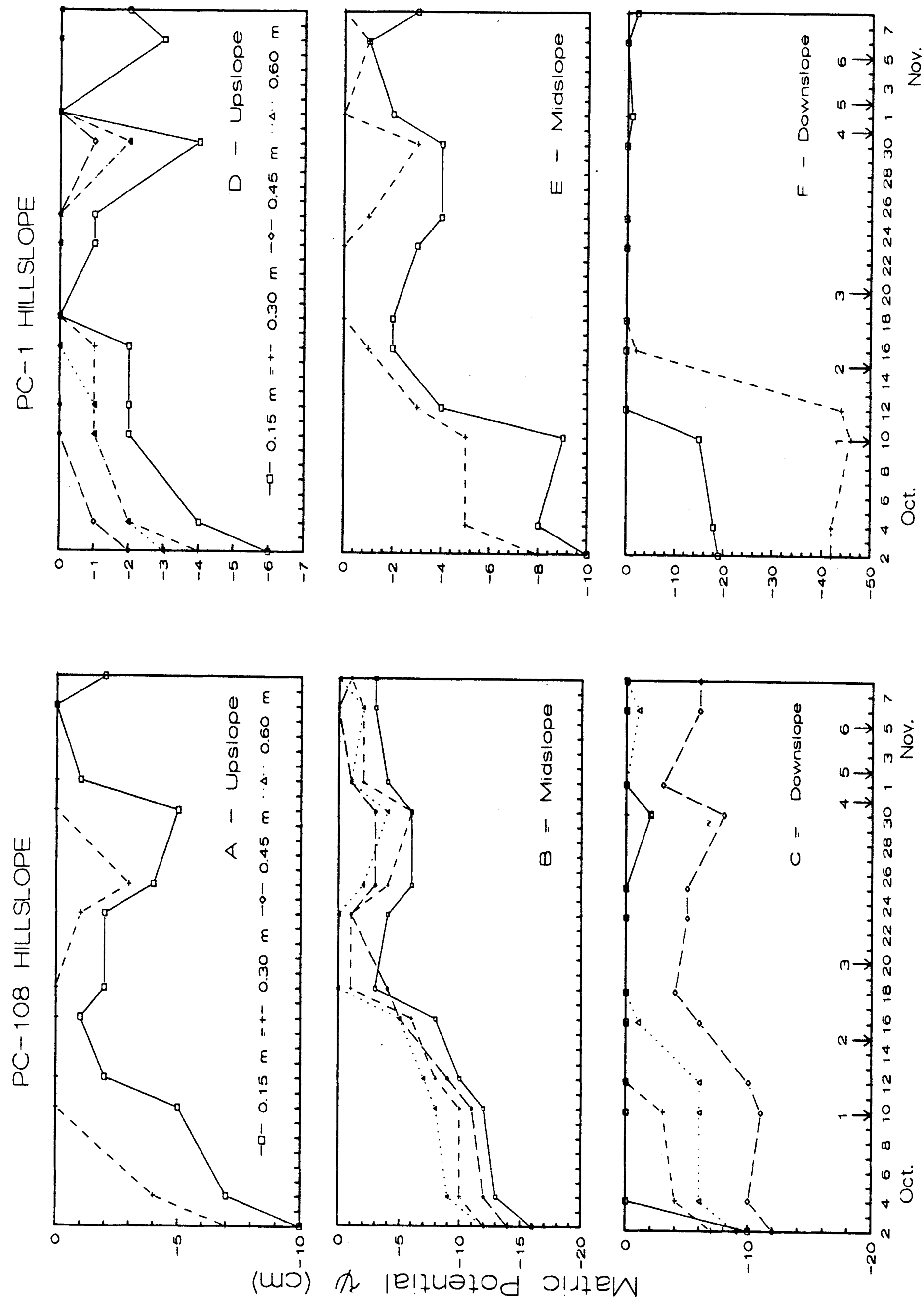

Fig. 3. Soil matric potential conditions for PC-1 hillslopes. Numbers indicate the respective storm events given in Table 1.

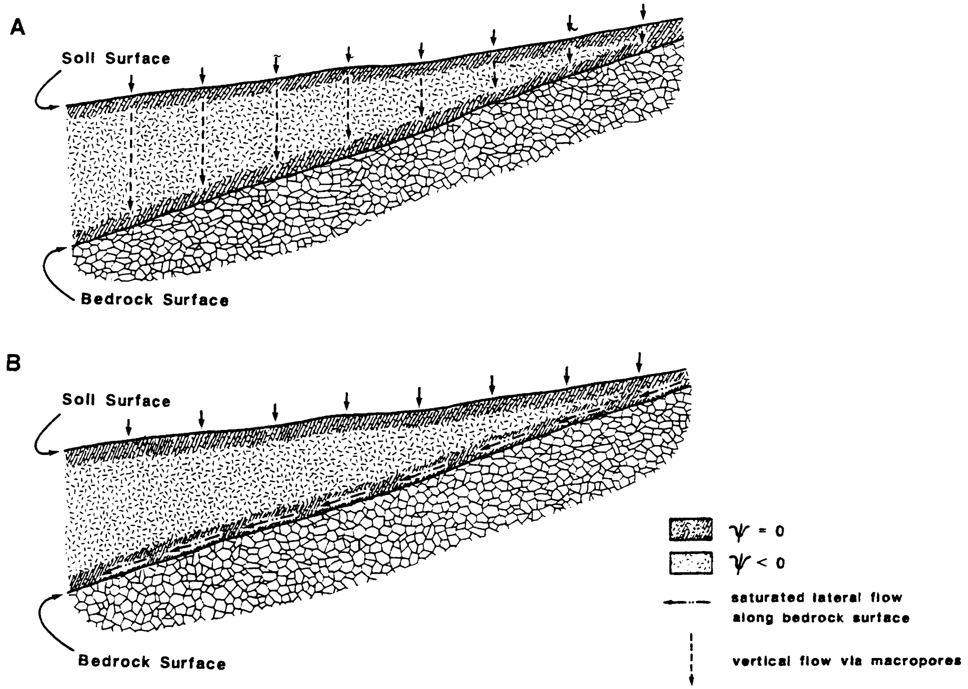

Fig. 4. Schematic representation of possible mechanisms to account for the matric potential ψ results: a) development of saturation at the soil/bedrock interface as a result of vertical macropore flow bypassing the unsaturated soil matrix; b) lateral supply of saturated flow at the bedrock surface from upslope areas. The cross-sections reflect the tendency for soils in PC-1 to increase in depth downslope.

0.15 m depths in early October preceded saturation at deeper points. This suggests that a saturated front moved vertically downward following the first two rainfall events. By October 18 at the PC-108 lower site, the shallow (0.15 m and 0.3 m) and deep (0.6 m) tensiometers indicated saturation, while the middle portion of the profile remained unsaturated. These results may reflect two mechanisms operating singly or in combination. First, passage of the wetting front may have saturated the upper 0.3 m of soil, below which water moved to the 0.6 m depth via unsaturated flow or macropores, resulting in low matric potentials at the 0.45 m depth (Fig. 4a). Rapid vertical motion of water through porous soils has been noted by others (Anderson and Burt 1982; Buttle and Sami 1990). The second possibility is that saturation of the 0.6 m depth occurred independently of saturation of the upper layers. This could have resulted if water had been laterally supplied from upslope areas along the impermeable bedrock (Fig. 4b).

The middle and upslope nests (Fig. 3) show similar trends at both sites. Unlike at the downslope nests, prolonged saturation of the upper soil did not occur at the PC-1 site. Saturation at the 0.15 m depth occurred during or shortly after the two largest rainfall events, but soils drained quickly (Fig. 3). The deeper tensiometers suggest extended periods of saturation at all middle and upslope sites. As saturation at these depths occurred independently of saturation at shallower depths, macropore flow may have by-passed the upper horizons and caused a saturated layer to develop on the impermeable bedrock. It is also possible that downslope flow along the bedrock was supplied to midslope sites, as saturation of deeper midslope tensiometers occurred at least two days after upslope saturation for both sites (Fig. 3).

Three significant observations can be drawn from the tensiometric results. First, soil moisture conditions were variable not only over the study period, but also with distance upslope. Second, it can be inferred that saturation of the deepest tensiometers resulted from development of a saturated layer above the bedrock. Vertically infiltrating water may have by-passed upper horizons and reached the bedrock surface. Third, it appears that downslope sites were supplied by lateral flow along the bedrock from further upslope.

Hillslope Response

Subsurface Flow – The hillslope response for the first storm differed from that of the succeeding events. Total output from Trench A for storm 1 was 360 ml, which represents only 0.001 mm or 0.07 % of event rainfall. Of this output, 72 % came from the organic/Ae horizon during the early part of the event. This was the only event during which this horizon responded. A 'thatched roof' mechanism could explain why the organic horizon responded during this relatively dry period. Ward (1984) describes how water could be transmitted laterally through a thatched roof made of straw without infiltrating through the base of the roof. Lateral flow is attributed to the alignment of the straw, which imparts a preferential permeability along the stems when a slope is present. Accumulations of organic matter (*e.g.* pine needles) at the soil surface could potentially act like a thatched roof under dry antecedent conditions. Runoff from the organic/Ae horizon during the first event would also be enhanced by hydrophobicity of the organic layer, since prolonged drought appears to promote water repellency in organic layers in forest soils (Wilson *et al.* 1990). As organic matter is usually in a state of decay, the integrity of the roof would be in doubt under wetter conditions. These conditions also serve to reduce the hydrophobicity of the organic layer (Wilson *et al.* 1990). The only other horizon to respond during storm 1 was the B horizon, which began to flow 24 h after the onset of rain. It is important to note that flow at the soil/bedrock interface did not occur. Although total precipitation was comparable to other events (Table 1), the small amount of discharge from the trench suggests that water infiltrated and was stored in the soil profile. Tensiometric data (Fig. 3) showed that the minimum antecedent moisture preceded this event and that the lower portion of the soil profile remained unsaturated during the storm.

Typical hillslope responses at Trench A to rainfall input are represented by

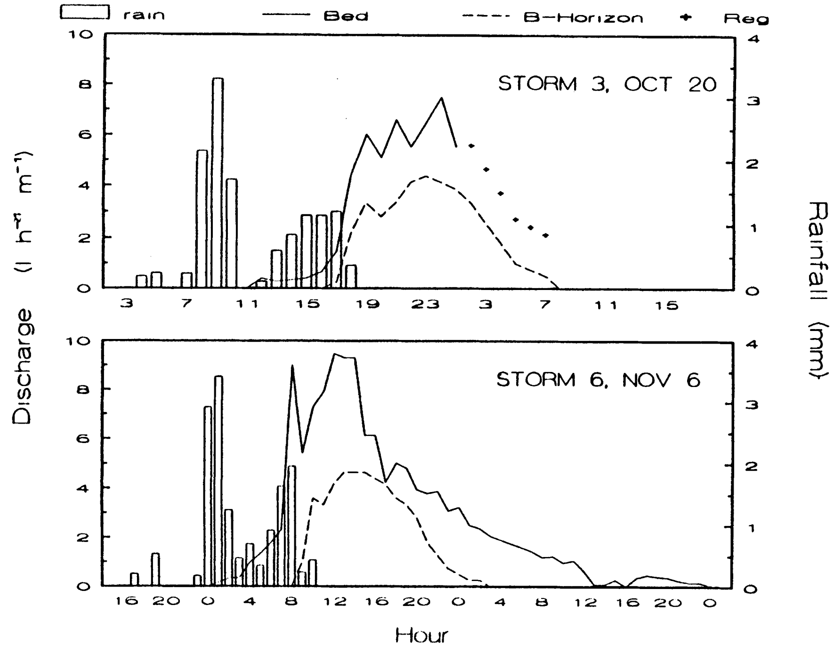

Fig. 5. Rainfall and typical subsurface flow response for Trench A. B-Horizon flow has been increased by 2 orders of magnitude to preserve scale. (Bed ≡ flow along soil/bedrock interface; + Reg ≡ points estimated by regression of bedrock surface flow on flow from the B horizon).

hydrographs from storms 3 and 6 (Fig. 5). They show that flow at the bedrock surface was the dominant discharge component for Trench A. In general, this component was two orders of magnitude larger than the B horizon flow, with peak flow from both layers being synchronous. It is possible, therefore, that flow from the B horizon tray was initiated by the rising of a saturated layer from the impermeable bedrock. However, two pieces of evidence suggest that flow from the B horizon was not solely a function of a rising saturated layer. The first is that the B horizon responded to input during event 1 without the occurrence of flow along the bedrock surface. Secondly, concentrations of parameters associated with mineral weathering (Ca, SiO_3, Mg) were similar in bulk flow samples from the B horizon tray and the bedrock surface during storm 6 (Table 2), although B horizon flow was relatively enriched in parameters associated with organic sources (K, DOC, NH_4 and NO_3). Increases in the concentration of organic compounds, such as DOC and organic Al complexes, in water draining upper soil horizons have been noted elsewhere (Cozzarelli *et al.* 1987, Lawrence *et al.* 1988, Swistock *et al.* 1989). In addition, Lozano *et al.* (1987) indicate that root densities and levels of K, DOC, NH_4 and NO_3 in the B horizon of these ortho humo-ferric podzols exceed those in the B/C or C horizons. Thus, the chemical signature of B horizon flow may be a

Table 2 – Bulk chemistry for Trench A flow during storm 6, Nov. 5.

	Ca	SiO_3	Mg (mg l^{-1})	K	DOC	NH_4	NO_3 (μg l^{-1})
Bedrock/soil	2.44	3.66	0.64	0.83	5.1	12	18
B Horizon	2.31	4.02	0.85	2.6	6.3	80	55

result of increased contact with organic material during the vertical transmission of water through the O/Ae horizon or the downslope movement of water as unsaturated flow along roots and root channels, as suggested by Beven and Germann (1982). Nevertheless, the overall contribution of such flow in the B horizon to the total pit discharge was minor relative to flow at the bedrock surface.

Comparison between Trenches – Trench B was installed following the second event in order to compare the hillslope response from a thin soil cover to that of the relatively deeper soil of Trench A. Soil depths from the area draining to Trench B were 0.24 m less, on average, than those from the Trench A drainage area. The trench face itself averaged 0.1 m in depth. Observation during storm events suggested that all flow from this trench was subsurface in nature and along the bedrock. The following discussion therefore compares Trench B response only to the bedrock response from Trench A.

Flow from both trenches commenced at the same time in response to rainfall (Fig. 6). However, the time from peak rainfall to peak discharge was from 2 to 13 h longer for Trench A. Further, recession rates for the one event with a complete record (event 6) were also quicker for the shallower trench. Areas of thin organic/Ae soil cover over bedrock are very extensive in the Canadian Shield. As has been shown, these areas rapidly develop a saturated layer over bedrock during rainstorms and then quickly drain. Runoff from these areas would then supply flow to the deeper soils of downslope areas, which is consistent with the mechanism suggested in Fig. 4b.

Comparison of discharge volumes from Trench A and Trench B (expressed as depths) shows that the total runoff response for the four events during which both trenches were operable was the same (Table 3). Runoff responses varied slightly on an event basis, but no clear pattern emerged.

What cannot be inferred directly from Fig. 6 or Table 3 are the processes by which water moves from the soil surface to the base of the profile or downslope. Intuitively, more water would be expected to go into storage on hillslopes with deep soils. Hence, more water should flow from the shallower Trench B than from Trench A. However, the runoff responses (Table 3) are similar for the two trenches and appear to be independent of total rainfall. A macropore mechanism could explain the observed discharge volumes, as subsurface flow via macropores does not require satisfaction of a large storage component.

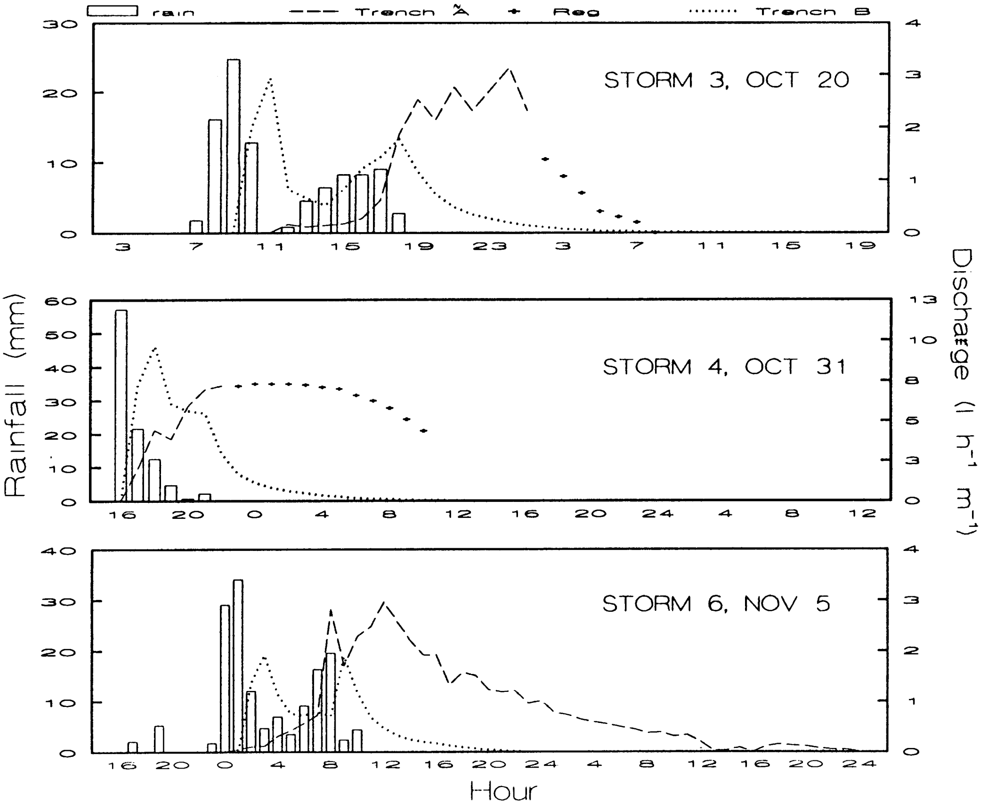

Fig. 6. Rainfall and typical flow response along the soil/bedrock interface for Trenches A and B. (+ Reg = points estimated by regression of bedrock surface flow at Trench A on flow from the B horizon at Trench A.)

Table 3 – Runoff depths and responses, Trenches A and B.

	Total Depth (mm)			Runoff Ratio	
	Rainfall (P)	Trench A (Q_A)	Trench B (Q_B)	Q_A/P	Q_B/P
* Storm 3	13.2	(0.7)	1.2	0.05	0.09
+ Storm 4	22.3	(1.9)	2.0	0.09	0.09
* Storm 5	6.7	(0.9)	0.7	0.14	0.11
Storm 6	15.2	(1.6)	1.2	0.11	0.08
Total	57.4	5.1	5.1	0.09	0.09

* missing 11+ h of data

\+ missing 6+ h of data

Bracketed values obtained by adding regressed values to measured volumes.

Simple calculations were made to see whether a Darcian mechanism could explain observed peak flow rates from Trench A. The average saturated hydraulic conductivity, K_S', was $4.0 \times 10^{-5} \pm 3.0 \times 10^{-5}$ m s^{-1} (n=16) for the soils in the Trench A drainage area, based on constant head permeameter measurements. There was no systematic change in conductivity with depth, as the K_S calculated separately from samples taken within 0.09 m of the bedrock surface was $3.8 \times 10^{-5} \pm 4.2 \times 10^{-5}$ m s^{-1} (n=8). The average bedrock slope for the lower 10 m of hillslope was 0.21. Assuming that flow from the B-horizon tray indicates that a saturated layer has reached this level, a minimum depth of saturation at the pit face during peak flows would have been 0.12 m, giving a total saturated area at the pit face of 0.38 m^2. Substituting the slope, saturated trench face area and average soil K_S into Darcy's equation gives a discharge of 10.8 l h^{-1}, while increasing K_S by one standard deviation gives a flux of 23.0 l h^{-1}. Both values are lower than the peak flows given in Table 4. It is not possible to explain peak discharge solely by Darcian flow even when the depth of saturation is assumed to exceed the minimum 0.12 m during peak flows. Using a saturated depth of 0.25 m (indicated by saturation of the deepest tensiometer at an upslope site with a soil depth similar to that at Trench A), discharges of 23.9 l h^{-1} and 41.8 l h^{-1} are obtained using the mean and mean + 1 SD hydraulic conductivities for the total soil layer, respectively. The lesser value is still smaller than the peak flow of four events, while the upper estimate is greater than four of the observed peak flows but still less than the peak discharge for storm 2. Therefore mechanisms other than matrix flow must have contributed significantly to the flow.

Macropores can serve as important conveyors of water in unsaturated conditions provided that the supply of water to the macropore exceeds the rate at which water can be extracted from the macropore by the soil matrix (Beven and Germann 1982). Since macropore flow was not measured directly, there is no conclusive evidence that the mechanism was important in generating subsurface flows. However, it has been measured in similar soil types (Espeby 1989a). We believe that macropores are most likely located immediately above the bedrock surface in these

Table 4 – Peak soil/bedrock interface discharges from Trench A. Bracketed values are estimates.

	Peak Discharge (l h^{-1})	Peak Discharge (mm h^{-1})	Total Rainfall (mm)
Storm 1	no response		14.3
Storm 2	98.0	2.9×10^{-4}	24.5
Storm 3	23.5	6.9×10^{-5}	13.2
Storm 4	(35.0)	(1.0×10^{-4})	22.3
Storm 5	(31.0)	(9.1×10^{-5})	6.7
Storm 6	29.2	8.6×10^{-5}	15.2

shallow soils, as postulated by Wels *et.al.* (1991). Total rainfall for storm 2 was the largest recorded; as well, soil matric potentials were near 0 cm prior to this event (Fig. 3), implying that hydraulic gradients drawing water from macropores into the soil matrix were low.

Taken together, these observations suggest that Darcian flow supplied runoff at the soil/bedrock interface during all events, but that contributions from macropore flow likely dominated discharge during the largest storm. Although the results imply a spatial variability in subsurface flow, and are somewhat inconclusive in regard to the nature of this flow, they show clearly that flow at the bedrock surface was the predominant pathway for water movement down the slope.

Significance of Hillslope Flow to Catchment Response

In order to assess the influence of subsurface bedrock flow on catchment discharge, hillslope responses were compared to discharge records from sub-catchment PC-108 (Fig. 7). The timing of the peak bedrock flow discharge and recession of flow from Trench A were strikingly synchronous with corresponding features of the PC-108 hydrograph. The Trench B hydrograph conformed much less, with rises, peak flows and recessions all occurring much earlier. This is not to say that subsurface flows from areas with very thin soil are not important in contributing to channel discharge. A small, yet noticeable rise in PC-108 discharge was observed shortly after peak discharge from Trench B during storm 3 (12:00). However, depending on the position of shallow soil zones, it is likely that most water discharging from such areas was shunted through the deeper soils flanking the PC-108 channel before reaching the stream. Therefore, subsurface flow from the deeper soils at Trench A probably provides a better index of hillslope contributions to PC-108 streamflow.

Based on this assumption, discharge from Trench A was used to calculate the approximate proportion of peak channel flow contributed by subsurface flow. Multiplication of peak fluxes per unit length at Trench A by a conservative estimate of 500 m for the PC-108 channel length under fall conditions, yielded subsurface flow contibutions ranging from 42 % to 85 % of channel discharge (Table 5). The largest contribution would have occurred during storm 2 (Oct. 15). Runoff

Table 5 – Estimated subsurface flow contributions to peak channel discharge.

	PC-108 (l h^{-1})	Trench A (l h^{-1} m^{-1})	Trench A × 500 m	Subsurface Percentage
Storm 2	18464	29.7	14848	85
Storm 3	7882	7.5	3750	48
Storm 4	12183	11.2	5591	46
Storm 5	7744	9.9	4952	64
Storm 6	11132	9.3	4650	42

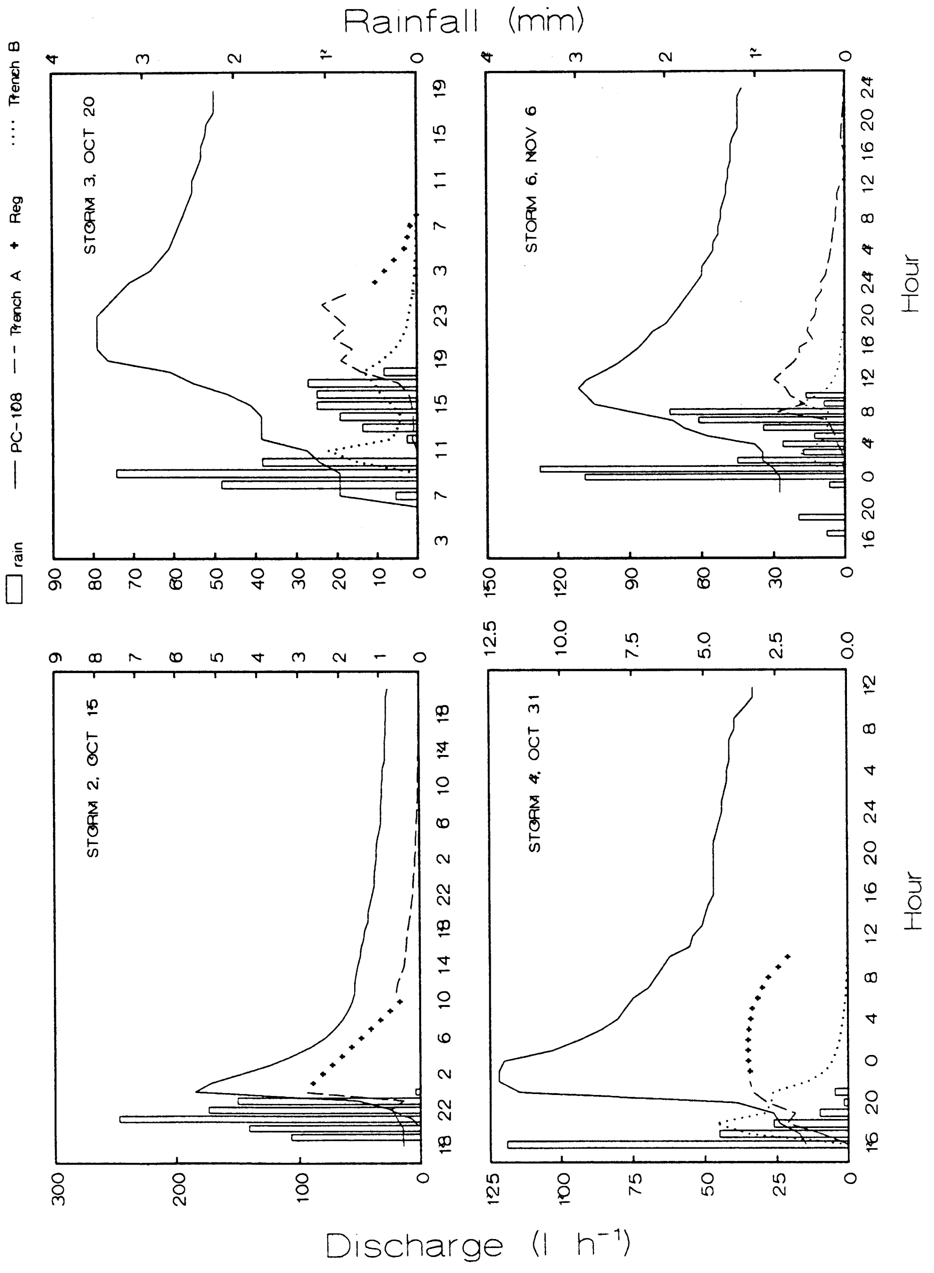

Fig. 7. Discharge from PC-108 and flow along the soil/bedrock interface for Trenches A and B. PC-108 discharge has been reduced by 2 orders of magnitude to preserve scale. (+ Reg = points estimated by regression of bedrock surface flow at Trench A on flow from the B horizon at Trench A.)

depths calculated for the contributing area above Trench A and for the total PC-108 watershed were also compared for the two largest storms. The watershed response to the 24.5 mm input of storm 2 was 5 mm (20.4 %) compared to response from the trench of 2.5 mm (10.2 %). For storm 4 (total input 22.3 mm), the watershed response was 5.3 mm (23.8 %) while the trench response was 1.9 mm (8.5 %).

These calculations show that subsurface flow along the bedrock surface is a significant contributor to peak storm flows and runoff yields in this watershed, in addition to its role in sustaining channel discharge, as suggested by Bengtsson (1988) for Scandinavian basins and Shibatani (1988) for this catchment. The results also fit with the hypothesis of Wels *et al.* (1991) that saturated macropore flow along the bedrock surface could explain much of the runoff response from PC-108 during spring melt. At the same time, it is clear that other mechanisms are also contributing to peak channel flow during rainstorms. The main additional contributor is probably direct precipitation onto saturated near-channel areas, as shown by Shibatani (1988) for the PC-1 watershed during snowmelt runoff.

Summary

This study investigated the significance of subsurface flow as a runoff generator in shallow soil Canadian Shield catchments. Previous work suggested that a zone of saturation can extend upwards from the impermeable bedrock of hillslopes in PC-1 towards the soil surface. Our results indicate that flow over bedrock was a large component of discharge from the monitored hillslope. Calculations show that the flow could not have been supplied entirely by Darcian flow through the soil matrix, but rather that a significant portion must have been supplied via macropore flow, most likely at the base of the soil layer. This supports the first hypothesis that flow along the soil/bedrock interface dominates the discharge from hillslopes of the shallow soil PC-1 watershed.

A comparison of the hillslope hydrographs with PC-108 discharge for a series of rainstorms show that the peak flows and recessions at the soil/bedrock interface were synchronous with PC-108 runoff. Between 42 and 85 % of PC-108 peak discharge was estimated to have been contributed by flow along the bedrock surface. Runoff depths from trenches were up to 50 % of runoff depths calculated for the entire PC-108 watershed. Therefore the second hypothesis, that this hillslope flow component is the major contributor to streamflow discharge during rain events, was also supported.

This research, besides supporting previous work, raises many questions as to the nature of subsurface flow in shallow soil Shield catchments. It highlights the need to design field techniques that will distinguish clearly between matrix and macropore flow. In the future it would be useful to determine if the relative importance of these mechanisms varies on a seasonal or even event basis. Field work such as this will advance our knowledge of hillslope processes in Canadian Shield catchments and aid in the development of realistic hydrological and hydrogeochemical models.

Acknowledgements

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Address:
Watershed Ecosystems Program,
Trent University,
Peterborough, Ont.,
Canada K9J 7B8.