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Runoff Processes on a Forested Slope on the Canadian Shield

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Throughfall reaching the ground surface on forested slopes may follow a variety of pathways to receiving water bodies, and travel times and chemical interactions between water and soil may differ between these pathways. We examine the controls that throughfall and pre-event soil water characteristics impose on: 1) separation of incident throughfall between flow over/through the soil's organic mat and subsurface flow; and 2) separation of subsurface runoff between bypassing flow via macropores and translatory flow through the soil matrix. Runoff response to summer and fall rainstorms in 1997 was examined for a forested slope in south central Ontario. Flow over and through the thin podzol soil cover was measured at a throughflow trench, while vertical profiles of soil water content were measured at various sites on the slope. Overland flow increased with throughfall intensity and decreased with antecedent soil wetness, implying that this pathway was most effective during drought conditions which promoted hydrophobicity of the organic layer. Vertical bypassing flow was directly related to throughfall intensity, but independent of pre-event soil water content on the slope. Subsurface runoff properties were also not related to antecedent soil wetness; however, strong association between throughfall intensity and slope runoff suggested that coupled vertical and lateral macropore flow controlled runoff generation during small-to-medium size events. Translatory flow displacement of pre-event soil water on the slope may increase in importance for larger events and greater antecedent wetness conditions than were observed in this study.

Introduction

The route that water follows on contacting the ground in forested basins controls both the time required for water to reach a receiving stream or lake and the chemical signature of that water. Throughfall reaching the forest floor is initially partitioned between surface and subsurface flow pathways. Most evidence indicates that runoff in forested basins is dominated by subsurface flow processes (Whipkey and Kirkby 1978). Large hydraulic conductivities, K_H, of forest soils and their apparent ability to infiltrate all but the most intense rainfalls (Freeze 1972) suggest that Horton overland flow rarely occurs in forest basins, or is restricted to sites that have undergone disturbance such as soil compaction during logging (Bonell 1993). Nevertheless, Horton overland flow in forested basins can occur in areas of exposed bedrock (Allan and Roulet 1994) or bare soil (Bonell and Williams 1986), or where focussed stemflow fluxes may locally exceed the soil's infiltration capacity (Herwitz 1986). Saturation overland flow in humid temperate forests is generally thought to be restricted to areas where the water table is close to the ground surface, such as riparian zones and hillslope concavities. Widespread saturation overland flow on forest slopes has also been observed in tropical regions where rainfall intensities can exceed the K_H of impeding soil layers located close to the surface, and the resultant perched water table may intersect and saturate the soil surface (Bonell 1993). A third form of overland flow involves the movement of water over and through the overlapping leaves and other organic debris that may completely "shingle" (Whipkey 1965) the forest floor. Water may move above and through the organic mat overlying mineral soil similar to the "thatched roof" analogy of Ward and Robinson (1990). This runoff is not strictly Horton overland flow, since throughfall intensities may not exceed the infiltration capacity of the underlying mineral soil. Few studies have explicitly examined such overland flow, and Whipkey (1965) suggested that it was unimportant in terms of total slope runoff. Nevertheless, such runoff occurs relatively frequently on some slopes (Peters 1994), and is of hydrochemical interest because it may undergo limited chemical interaction with the soil and pre-event soil water (Buttle and Peters 1997) while supplying dissolved organic carbon, DOC, to receiving waters as a result of litter leaching (Hinton *et al.* 1998).

Throughfall infiltrating the mineral soil surface may subsequently be separated into translatory flow (displacement of pre-event soil matrix water deeper into the profile and/or downslope by event water inputs (Hewlett and Hibbert 1967)) and bypassing flow (rapid movement of event water to depth and downslope via preferential pathways such as macropores (Beven and Germann 1982)). The degree of partitioning of incoming water between these two processes can have important implications for basin hydrochemistry. It is often assumed that relatively longer water residence times associated with translatory flow offer greater opportunity for chemical interaction between precipitation, soil and resident water than does bypassing flow, which may reach the receiving stream or lake having undergone comparatively little chemical alteration (Nielsen *et al.* 1986).

The role of the organic layer in diverting incident throughfall downslope and the subsequent partitioning of infiltrating water between translatory and macropore flow can be hypothesized to depend on both input and pre-event soil wetness characteristics. Assuming that flow over and through the organic mat occurs when water delivery exceeds the ability of the organic mat to infiltrate water vertically to the underlying mineral soil, generation of such overland flow should be directly related to flux rates to the surface (*hypothesis 1*). Water repellency can be induced in forest soils by litter and plant exudates, and may be enhanced by drought conditions (Burch *et al.* 1989; Wilson *et al.* 1990). Continuous vertical water films through the organic mat may develop less readily for a dry relative to a wet litter layer, promoting lateral movement of water downslope rather than vertically to the underlying mineral soil. Thus, generation of flow over and through the organic mat on forested slopes may be inversely related to pre-event soil wetness (*hypothesis 2*). Water entry into soil macropores occurs when surface inputs exceed the ability of the soil matrix to infiltrate water, while wetter matrix conditions reduce lateral abstractions of macropore flow into the surrounding soil and allow bypassing flow to reach greater depths in the profile (Beven and Germann 1982). Therefore generation of vertical bypassing flow via macropores is directly related to both water flux at the soil surface and pre-event soil wetness (*hypothesis 3*). Slope runoff via either macropore or translatory flow should also increase with pre-event soil wetness, the former because wetter soils extract less water from lateral macropores into the surrounding matrix and the latter because translatory flow is most effective in wetter soils with reduced capacity to store inputs (Hewlett and Hibbert 1967). We suggest that the relative importance of these processes to subsurface runoff can be assessed by the strength of the association between runoff and throughfall characteristics. Thus, subsurface runoff will be directly related to throughfall intensity if macropore flow is the dominant runoff-generating process (*hypothesis 4*), since larger input fluxes at the soil surface are needed to initiate macropore flow (Beven and Germann 1982). Conversely, subsurface stormflow will be directly related to throughfall depth if translatory flow is the dominant runoff-generating process (*hypothesis 5*), given that displacement of pre-event soil water should increase with the amount of water entering the soil. The purpose of this paper is to test these hypotheses using measurements of runoff generation from a forested slope.

Study Area and Methods

A shallow-soil slope on the Canadian Shield in south-central Ontario (45°11'N, 78°50'W) was examined. The site is within the Plastic Lake-1 (PC-1) basin, the hydrochemistry of which has been monitored by the Ontario Ministry of Environment (OME) since 1985. Mean annual precipitation is 1,100 mm, 73% of which is rain.

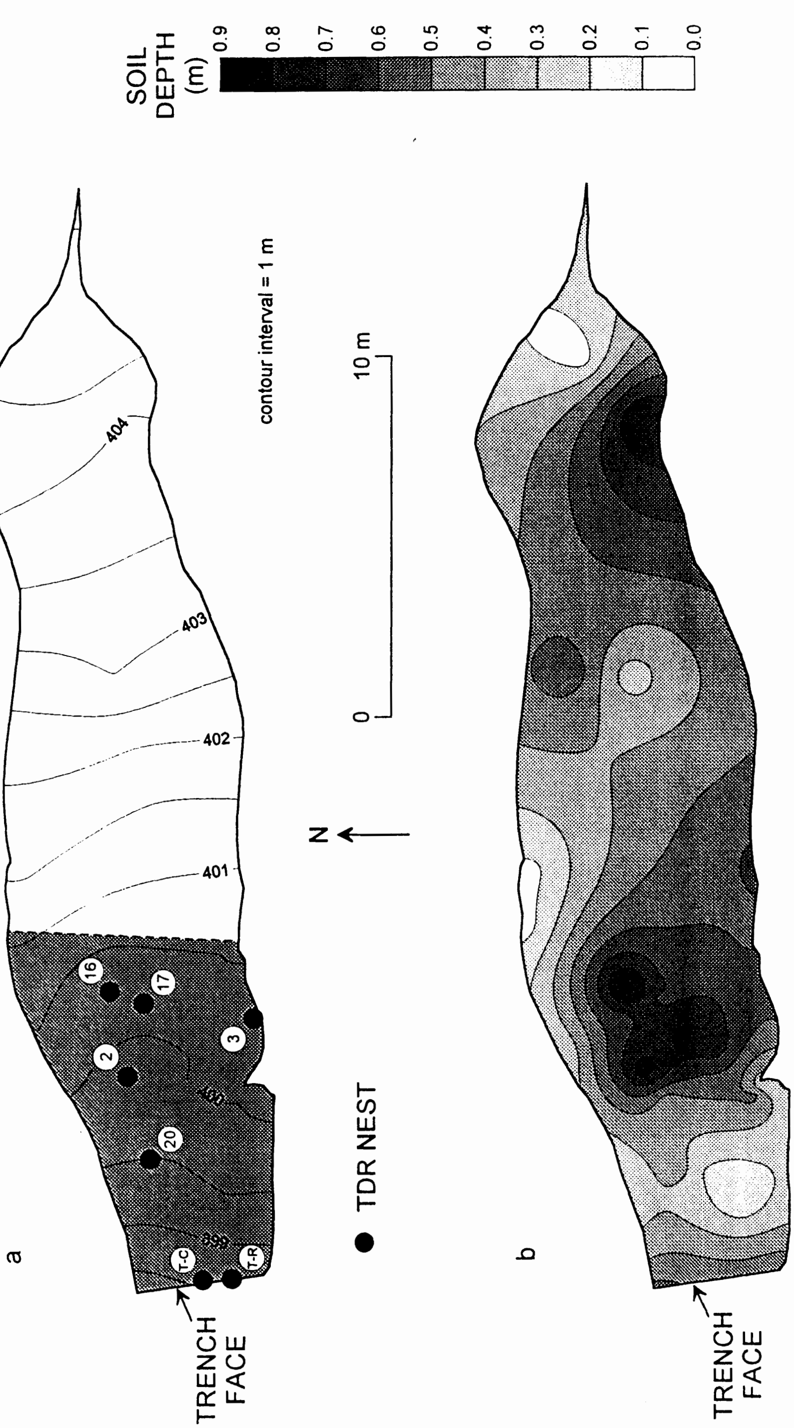

Fig. 1. Microcatchment drained by the throughflow trench on the study slope: (a) bedrock surface topography and location of TDR nests (shaded portion of slope encompasses area used to map saturated layer extent and thickness in Fig. 7); (b) soil depth in the microcatchment.

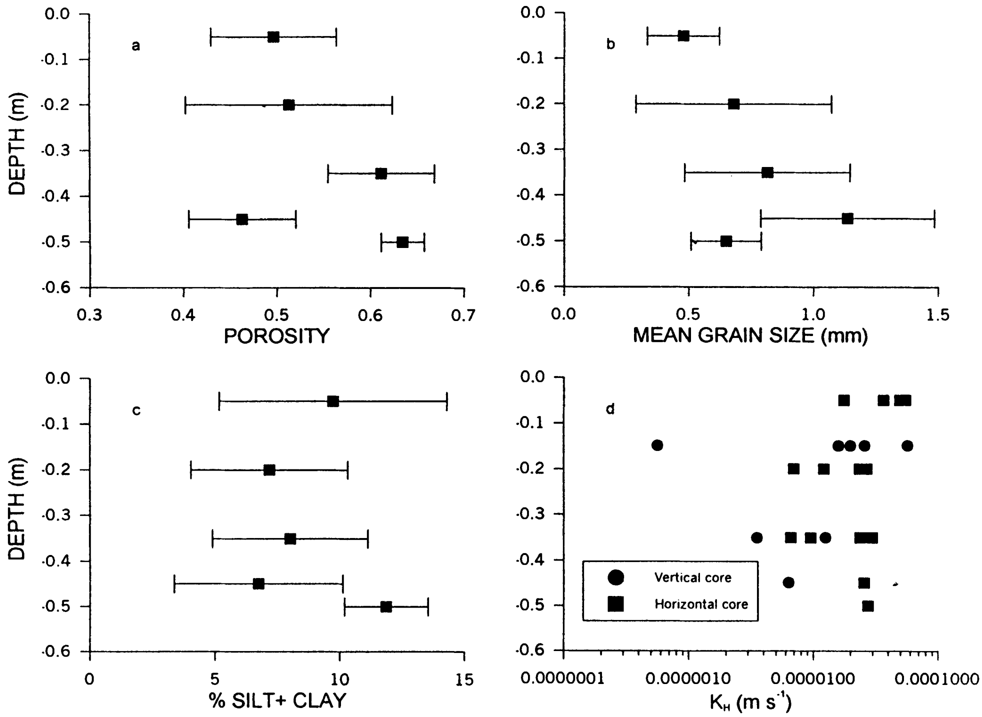

Fig. 2. Vertical profiles of soil properties (mean ±1 standard deviation) measured from soil cores extracted adjacent to the microcatchment: (a) soil porosity; (b) mean grain size; (c) % of soil consisting of silt and clay; and (d) vertical and horizontal saturated hydraulic conductivity of the soil matrix, K_H. Symbols are plotted at the core mid-point depths

The slope is slightly convex, has mean gradient of 0.14 and is underlain by granitic gneiss. Soil cover consists of weakly-developed orthic humo-ferric and orthic ferro-humic podzols, with depths ranging from 0 to 0.9 m (Fig. 1). The slope's morphology and thin soil cover is typical of a substantial portion of the Canadian Shield landscape in central Ontario (Dillon *et al.* 1991). Mean soil horizon thicknesses are: LFH – 4.9 cm; A – 2.6 cm; B1 – 20 cm; B2 – 23.6 cm (LaZerte and Scott 1996). Soil properties measured adjacent to the slope indicate porous, sandy, conductive soils with no marked change in matrix K_H with depth (Fig. 2). This, combined with the presence of vertical soil macropores (Buttle and House 1997), suggests that lateral movement of soil water above an impeding layer in the profile is unlikely. Previous work indicates that most runoff from such slopes flow tends to occur at the base of the soil profile in a thin zone above the bedrock surface (Wels *et al.*1991; Peters *et al.* 1995). Vegetation consists mainly of conifers (white pine, eastern hemlock and white cedar), with some deciduous species (white birch, red oak, striped maple).

Table 1 – Macroporosity, soil depth and location of TDR probes at the instrumented sites.

SITE	MACROPOROSITY (% OF SOIL VOLUME)	SOIL DEPTH (m)	TDR PROBE DEPTHS (m)
2	0.02190	0.76	0.15, 0.3, 0.4, 0.5
3	0.00087	0.51	0.15, 0.3, 0.45
16	0.00654	0.87	0.15, 0.3, 0.45, 0.6, 0.7
17	0.00831	0.6	0.15, 0.3, 0.45, 0.6
20	0.01210	0.33	0.1, 0.2
Trench Centre	-	0.5	0.1, 0.2, 0.3, 0.4
Trench Right	-	0.5	0.1, 0.2, 0.3, 0.4

A 5.5 m section of 5.08 cm i.d. ABS tubing was cut in half lengthwise and suspended under the forest canopy ~0.75 m above the ground surface. Throughfall collected in the trough drained to a tipping bucket recorder. Neary and Gizyn (1994) reported that stemflow accounted for only ~2% of total precipitation in PC-1, and thus was not measured. A throughflow trench 3.4 m in length was excavated to bedrock to monitor slope runoff. The microcatchment defined by the trench had an area of 151 m^2 (Fig. 1). Flow was captured at the soil-bedrock interface, at an intermediate level *(INT)* ~0.1 m above the bedrock surface, and at the base of the organic-*Ae* horizon, *Ae*, using throughflow troughs connected to tipping buckets. The *Ae* trough captured runoff moving through the organic-*Ae* horizon as well as any overland flow. All tipping buckets (throughfall, runoff) were connected to a Campbell 21X data logger that recorded fluxes over 30 minute intervals.

Five sites on the lower portion of the microcatchment were instrumented with time domain reflectometry, TDR, probes at various depths (Fig. 1, Table 1) to measure soil water content, θ. Sites were selected to represent the range of soil macroporosity (fraction of soil volume consisting of pores with radii ≥ 0.5 mm) measured on the slope using a tension infiltrometer (Buttle and McDonald, submitted). TDR probes were also inserted into the throughflow trench face at various depths at two locations (Trench Centre [T-C] and Trench Right [T-R]). All TDR probes were linked to a Campbell CR10 data logger, and θ was averaged over 30 minute intervals.

Pre-event soil water depth on the slope was estimated by defining five soil layers (0 – 0.175 m, 0.176 – 0.35 m, 0.351 – 0.475 m, 0.476 – 0.65 m, 0.651 – 0.9 m), determining the fraction of slope area covered by each layer, and combining these values with the mean pre-event θ in each layer

$$S_p = \sum_{i=1}^{n} (\bar{\theta}_i z_i f_i) \tag{1}$$

where S_p = pre-event soil water depth on slope (m), n = number of soil layers, $\bar{\theta}_i$ = mean pre-event soil water content in soil layer i ($m^3\ m^{-3}$), z_i = thickness of layer i

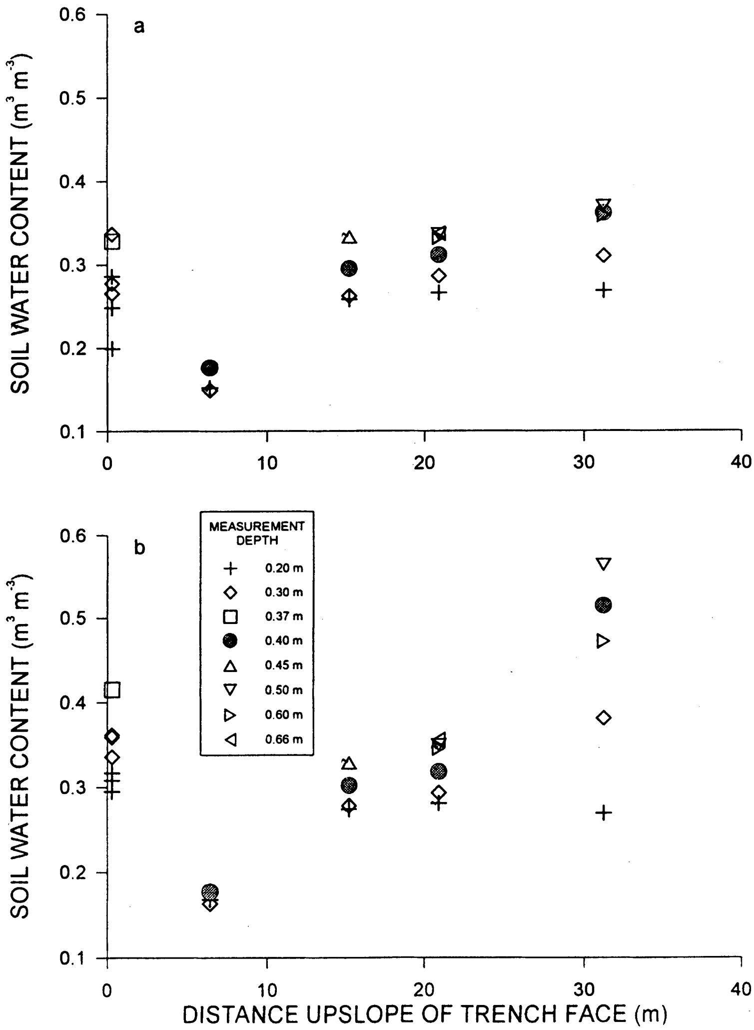

Fig. 3. Soil water contents measured using a neutron probe at various depths and distances upslope of the trench face (Peters 1994) immediately before (a) and after (b) a 44.5 mm rainfall on the microcatchment in 1991.

(m), and $f_i \equiv$ fraction of slope covered by soil layer i. We assume that TDR measurements made near the base of the microcatchment are representative of upslope θ conditions. This is supported by neutron probe measurements of θ in 1991 at access tubes located various distances upslope of the trench face (Peters 1994; Buttle and Peters 1997), where θ at a given depth immediately upslope of the trench face was similar to that observed at other locations in the microcatchment before and after a 44.5 mm rainfall (Fig. 3).

Table 2 – Comparison of throughfall and runoff characteristics for flow over and through the organic layer (*Ae*) and above the soil-bedrock interface (*BR*) for the monitored microcatchment from this and previous studies.

	Peters (1994) and Goodyear (1997)	This study
Number of monitored events	42	15
Mean throughfall (± s.d.[1]) (mm)	13.1 ± 14.0	11.1 ± 6.4
Maximum throughfall (mm)	71.2	22.1
Mean *Ae* runoff depth (± s.d.) (mm)	0.002 ± 0.006	0.013 ± 0.021
Maximum *Ae* runoff depth (mm)	0.034	0.077
Minimum *Ae* runoff depth (mm)	0.0	0.0
Mean *Ae* runoff coefficient (± s.d.)	0.0002 ± 0.0004	0.0009 ± 0.0011
Maximum *Ae* runoff coefficient	0.0023	0.0042
Minimum *Ae* runoff coefficient	0.0	0.0
Mean *BR* runoff depth (± s.d.) (mm)	2.099 ± 9.022	0.150 ± 0.305
Maximum *BR* runoff depth (mm)	57.334	1.169
Minimum *BR* runoff depth (mm)	0.0	0.0
Mean *BR* runoff coefficient (± s.d.)	0.0328 ± 0.1547	0.0085 ± 0.0166
Maximum *BR* runoff coefficient	0.8053	0.0636
Minimum *BR* runoff coefficient	0.0	0.0

1 s.d. – standard deviation

Results and Discussion

Throughfall

Fifteen throughfall events greater than 1 mm depth were recorded during the summer and fall of 1997. Depths and peak 30-minute intensities ranged from 4.4 to 22.1 mm and1.5 to 32.6 mm h^{-1}, respectively. Throughfall depths and peak intensities were significantly associated ($r = 0.53$, $p = 0.042$), so that both variables were not used concurrently in subsequent statistical analyses of runoff results. Maximum throughfall recorded in 1997 was much less than the maximum 10 yr 24-h rainfall (68 mm) from a precipitation station 250 m away, and was well below the maximum throughfall recorded in previous work on this slope (Table 2). However, there was a similar frequency distribution of recorded throughfalls compared to the long-term rainfall record for events of less than 15 mm.

Point Infiltration Processes

The θ response to throughfall is compared for sites representing maximum and minimum macroporosities on the slope (Table 1). An artificial irrigation experiment (Buttle and McDonald submitted) indicated that infiltration at the most macroporous site (Site 2) was via bypass flow, while the least macroporous site (Site 3) was dominated by translatory flow. Other instrumented sites exhibited responses between these extremes.

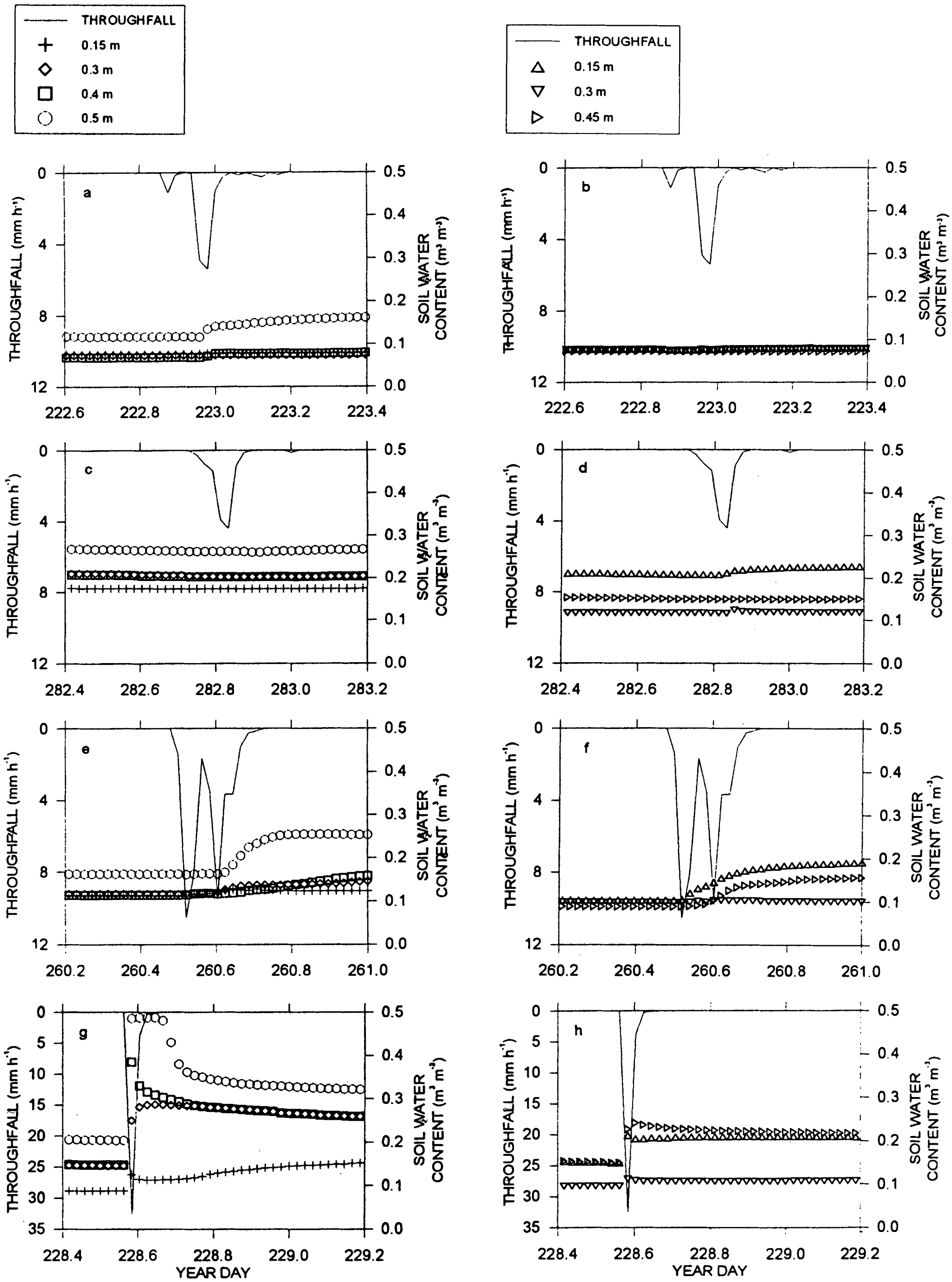

Fig. 4. Temporal variations in throughfall input and soil water content measured at various depths for Sites 2 (a, c, e and g) and 3 (b, d, f and h) during selected events.

The Year Day (YD) 222 event had small antecedent wetness (34 mm), throughfall depth (6.7 mm), and peak throughfall intensity (5.4 mm h^{-1}). Site 2 exhibited a slight increase in θ at the base of the soil profile coincident with peak intensity, suggesting minor bypass flow to depth. There was no θ response higher in the profile, while Site 3 θ showed no response at any depth (Fig. 4 a,b). The YD 282 event had a similar throughfall depth (5.7 mm) and peak throughfall intensity (4.4 mm h^{-1}) but much greater antecedent wetness (92 mm). Site 2 showed no response from the TDRs at any depth while there was a slight increase in near-surface θ at Site 3 (Fig. 4 c,d). This suggests that bypass flow does not vary with antecedent wetness for minor throughfall events of small intensity.

The YD 260 event had moderate antecedent wetness (55 mm), large throughfall depth (21.7 mm), and moderate peak throughfall intensity (10.5 mm h^{-1}). There was a minor increase in θ in the upper soil but θ at the profile base rose rapidly following the second throughfall peak. Bypass flow appears to have been more pronounced than for YD 222, possibly in response to wetter soil, larger throughfall inputs, and/or greater throughfall intensity. Site 3 showed an initial θ response to throughfall in near-surface soil and some evidence of bypassing to depth. However, bypassing was not as pronounced as at Site 2 (Fig. 4 e,f). The YD 228 event also had moderate antecedent wetness (64 mm) and large throughfall depth (18.4 mm), although peak throughfall intensity was the greatest observed in 1997 (32.6 mm h^{-1}). There was a minor increase in θ in the upper soil at Site 2, while θ at all other depths responded rapidly to peak throughfall. Comparison with the other events suggests that throughfall intensity is main control on the degree of bypassing at this site. Site 3 showed rapid θ responses to throughfall near the soil surface and at the base of the profile similar to the YD 260 response. Unlike the YD 260 response, the increase in θ was greater at the base of the profile compared to near-surface soil, implying increased bypass flow at this site in response to greater peak throughfall intensity.

Results support Buttle and McDonald's (submitted) conclusion that the fraction of water that bypasses the soil matrix during infiltration at a point increases with soil macroporosity. Nevertheless, even sites with small macroporosities (Site 3) exhibited some degree of bypassing flow during infiltration. Results partly support *hypothesis 3* in that generation of vertical bypassing flow appears directly related to water flux at the soil surface. However, preferential flow in these soils appears to be independent of pre-event soil water content, and Bouma (1991) notes that bypass flow may be enhanced in dry soils that develop water repellent properties.

Hillslope Runoff – Overland Flow

The slope was never saturated to the ground surface during any event, while peak throughfall intensity observed in 1997 (32.6 mm h^{-1}, 9.1×10^{-6} m s^{-1}) was less than the mean vertical K_H of the near-surface soil matrix (2.4×10^{-5} m s^{-1} ± 2.1×10^{-5} m s^{-1}, Fig. 2d). Thus, runoff captured by the *Ae* trough was generated as flow over the organic layer and lateral flow through the layer rather than by saturation or Horton

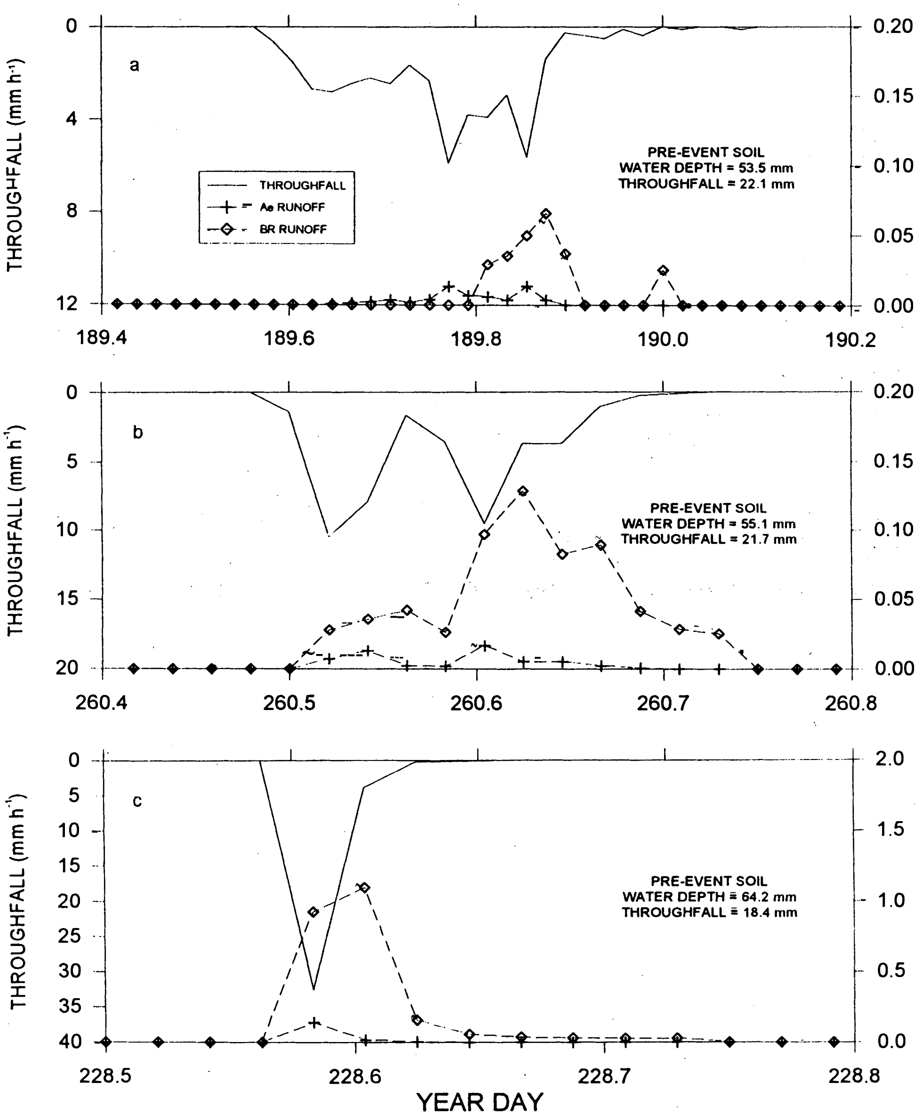

Fig. 5. Runoff hydrographs for events with similar throughfall and pre-event soil water depths, but increasing peak 30-minute throughfall intensity.

overland flow. *Ae* runoff occurred in response to major throughfall peaks (Fig. 5), beginning shortly after throughfall initiation and ceasing when throughfall intensity dropped. *Ae* runoff depths and runoff coefficients (*Ae* runoff/throughfall depth) in 1997 exceeded those observed on the slope by Peters (1994) and Goodyear (1997) (Table 2); nevertheless, runoff over and through the organic layer was small and

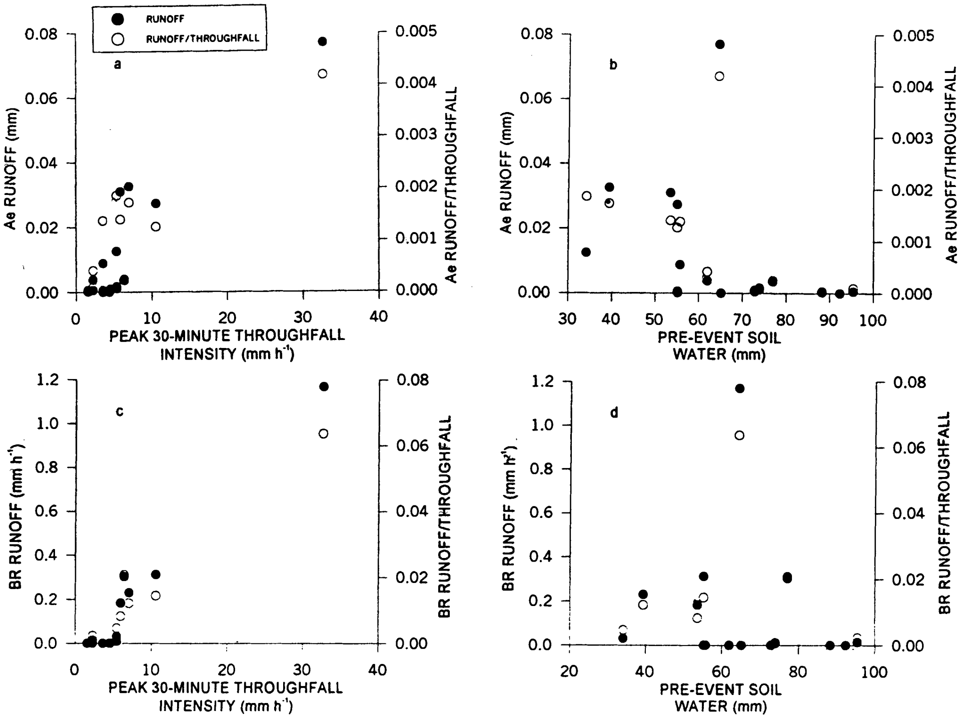

Fig. 6. Runoff response *vs.* peak 30-minute throughfall intensity and pre-event soil water depth on the slope.

Table 3 – Best-fit regression relationships between runoff depths (Y_1) and runoff coefficients (Y_2) and peak 30-minute throughfall intensity (X). Regression equations were determined both with and without the maximum runoff depth or runoff coefficient observed in 1997.

	BEST-FIT REGRESSION EQUATION	R^2	Significance level
Ae RUNOFF			
Including maximum runoff depth	$Y_1 = -3.6\times10^{-3} + 2.6\times10^{-3}X$	0.83	0.0001
Not including maximum runoff depth	$Y_1 = -8.7\times10^{-3} + 3.3\times10^{-3}X$	0.49	0.0053
Ae RUNOFF/THROUGHFALL			
Including maximum runoff coefficient	$Y_2 = -1.5\times10^{-5} + 1.3\times10^{-4}X$	0.73	0.0001
Not including maximum runoff coefficient	$Y_2 = -1.6\times10^{-5} + 1.6\times10^{-4}X$	0.27	0.0545
BR RUNOFF			
Including maximum runoff depth	$Y_1 = -1.1\times10^{-1} + 4.0\times10^{-2}X$	0.95	0.0001
Not including maximum runoff depth	$Y_1 = -1.2\times10^{-1} + 4.3\times10^{-2}X$	0.67	0.0003
BR UNOFF/THROUGHFALL			
Including maximum runoff coefficient	$Y_2 = -5.5\times10^{-3} + 2.1\times10^{-3}X$	0.93	0.0001
Not including maximum runoff coefficient	$Y_2 = -5.6\times10^{-3} + 2.1\times10^{-3}X$	0.55	0.0023

never comprised more than 0.5% of throughfall. This agrees with Whipkey's (1965) observation that flow over and through the litter layer is a minor component of total slope runoff. *Ae* runoff depths and runoff coefficients were both strongly associated with peak 30-minute throughfall intensity (Fig. 6a), and to a lesser extent with throughfall depth. Best-fit regression equations between runoff depth, runoff coefficient and peak 30-minute throughfall intensity were highly significant (Table 3), although R^2 values may have been unduly influenced by the maximum runoff depth and runoff coefficient observed in 1997 (Fig. 6a). Removal of these maxima gave a highly significant relationship between *Ae* runoff and peak throughfall intensity, while the statistical significance of the revised equation for *Ae* runoff coefficient *vs.* peak throughfall intensity was slightly in excess of the $p = 0.05$ level. Results support *hypothesis 1*: generation of flow over and through the organic mat on forested slopes is directly related to throughfall flux.

Overland flow occurred at relatively small throughfall intensities, and total slope runoff was dominated by *Ae* flow for events with less than 10 mm of throughfall and peak throughfall intensities less than 5 mm h^{-1}. Such runoff may relate to the hydrophobicity of dry organic matter (Burch *et al.* 1989; Wilson *et al.* 1990) which promotes flow over and through the organic "thatch". Little or no flow at the *Ae* trough occurred when pre-event soil water depth exceeded 65 mm (Fig. 6b). When runoff events with throughfall depths greater than 10 mm and peak throughfall intensities greater than 5 mm h^{-1} are examined, *Ae* runoff as a fraction of total slope runoff was inversely related to pre-event soil water depth ($r = -0.77$, $p = 0.0097$). As the soil (and presumably the overlying organic layer) gets wetter, more throughfall appears to be directed vertically into the underlying mineral soil. This supports *hypothesis 2*: generation of runoff over and through the organic mat on forested slopes is inversely related to pre-event soil wetness.

Hillslope Runoff – Subsurface Flow

Runoff at the soil-bedrock interface and from the *INT* trough was combined, since Peters *et al.* (1995) indicated that the latter was simply the upper portion of bedrock flow that was recorded when the saturated layer, initiated at the bedrock surface, rose above the elevation of the *INT* trough. This combined flow (*BR* runoff) supplied more than 70% of the slope's total runoff response for throughfall depths greater than 10 mm and peak throughfall intensities greater than 5 mm h^{-1}. *BR* runoff depths in 1997 were much smaller than those in previous years (Table 2), which reflects smaller throughfall events and very dry soil conditions in 1997. Flow at the soil-bedrock interface responded quickly to throughfall inputs to the forest floor, with time lags between peak throughfall and peak runoff in the order of 0.5 to 1 h (Fig. 5). This rapid response suggests that subsurface runoff was generated by bypass flow via macropores rather than translatory displacement of pre-event soil water. *BR* runoff continued after *Ae* runoff ceased, although *BR* runoff generally stopped within 2 hours of the end of throughfall.

Neither *BR* runoff depth or runoff coefficient was related to pre-event soil water depth (Fig. 6d). Runoff depth was significantly associated with peak 30-minute throughfall intensity ($r = 0.98$, $p = 0.0001$) and to a lesser extent with throughfall depth ($r = 0.60$, $p = 0.0177$), as were the runoff coefficients ($r = 0.96$, $p = 0.0001$; $r = 0.57$, $p = 0.028$, respectively). Stronger correlations between *BR* runoff depths and runoff coefficients and peak throughfall intensity relative to throughfall depth, and the association between vertical preferential flow via macropores and peak throughfall intensity independent of θ conditions in the soil matrix (Fig. 4), suggest that macropore rather than translatory flow dominated runoff generation (*hypothesis 4*). Intense throughfalls produced more *BR* runoff and translated a greater fraction of throughfall into *BR* runoff (Fig. 6c), and regression relationships in Table 3 remained statistically significant even when the maximum runoff depth and runoff coefficient observed in 1997 were removed from the data set. The importance of bypassing flow to subsurface runoff from the slope is consistent with reactive and non-reactive tracer studies on this microcatchment (Peters *et al.* 1995; Buttle and Peters 1997). These indicated that some water infiltrating the microcatchment soils moved rapidly via macropores vertically to the bedrock surface and laterally along the soil-bedrock interface. Nevertheless, this work also showed that a 44.5 mm rainfall resulted in pre-event water contributing ~75% of total slope runoff. Pre-event soil water depth for this event (124 mm) was much greater than was observed in 1997 (Fig. 6), and suggests that translatory flow may become a more important runoff generating process on the slope as both event size and antecedent wetness increases, consistent with *hypothesis 5*.

The greater importance of throughfall intensity relative to throughfall depth in explaining both overland flow and subsurface runoff on the slope contradicts Hewlett *et al.* (1977), who found that rainfall intensity was of little use in predicting stormflow from forested basins in the eastern USA relative to such factors as rainfall depth, antecedent wetness, season and rainfall duration. The contradiction may be the consequence of moving from slope to basin scales, where stormflow increasingly integrates outputs from a range of processes (macropore flow, translatory flow, Horton overland flow, saturation overland flow, groundwater contributions), some of which may have little or no association with input intensity.

TDR measurements showed temporary saturation of the soil profile base at various locations on the lower portion of the slope during some events (*e.g.* Fig. 4g), while soil overlying the bedrock surface immediately upslope of the trench face was saturated as subsurface flow exited the microcatchment. Similar saturated zones have been observed in other studies that have studied subsurface stormflow using throughflow trenches (*e.g.* Whipkey 1965; Weyman 1973), and may result from the presence of the trench itself in distorting the natural flow net on the slope and inducing an artificial saturated wedge upslope of the trench (Atkinson 1978). However, soil overlying the bedrock surface was unsaturated prior to each event in 1997, and observations elsewhere in the basin indicate the occurrence of a saturated layer

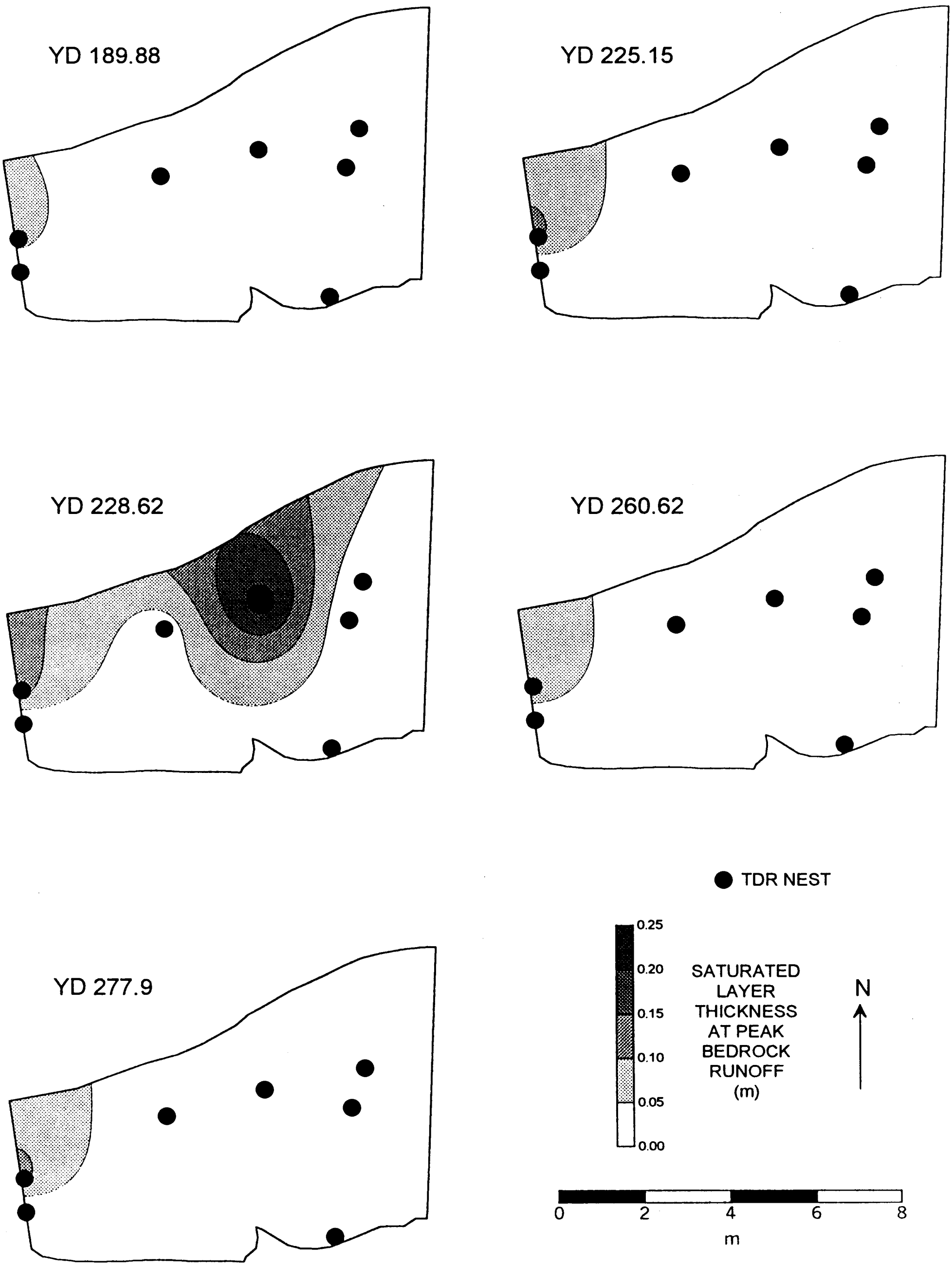

Fig. 7. Estimated extent and thickness of the saturated layer overlying the bedrock surface at the time of peak *BR* runoff for events that produced significant amounts of *BR* runoff.

above the soil-bedrock interface during rainfall and snowmelt (Renzetti *et al.* 1992). Peters' (1994) neutron probe measurements of θ on the slope (Fig. 4b) indicate that the lower soil profile can become saturated (θ ≈ soil porosity, see Fig. 2) at sites well upslope of the likely extent of any artificial saturated wedge induced by the trench itself. Thus, we feel that the trench had a minor effect on subsurface flow pathways on the slope, and that the saturated layer detected by the TDR probes developed naturally during the 1997 throughfall events. Buttle and McDonald (1997) hypothesized that the degree of coupling between vertical and lateral preferential pathways on the slope depends on the spatial extent of this saturated layer upslope of the trench face. Saturation of the base of the soil profile immediately above the bedrock surface occurred by the rapid vertical movement of infiltrating water to depth via macropores, similar to the mechanism proposed by McDonnell (1990). Tracer behaviour in soil water and runoff observed during artificial irrigations of the slope suggested that upslope extension of this saturated layer allowed a greater amount of water infiltrating via vertical macropores to be quickly transferred down the slope (Buttle and McDonald 1997).

This process was examined using θ *vs.* depth profiles for each TDR nest to estimate presence and thickness of basal saturation of the soil profile at the time of peak *BR* runoff, assuming that saturation occurred at θ greater than or equal to 0.4. These point thicknesses were then interpolated using kriging, and Fig. 7 shows the estimated saturated layer extent and thickness for major *BR* runoff events. The saturated

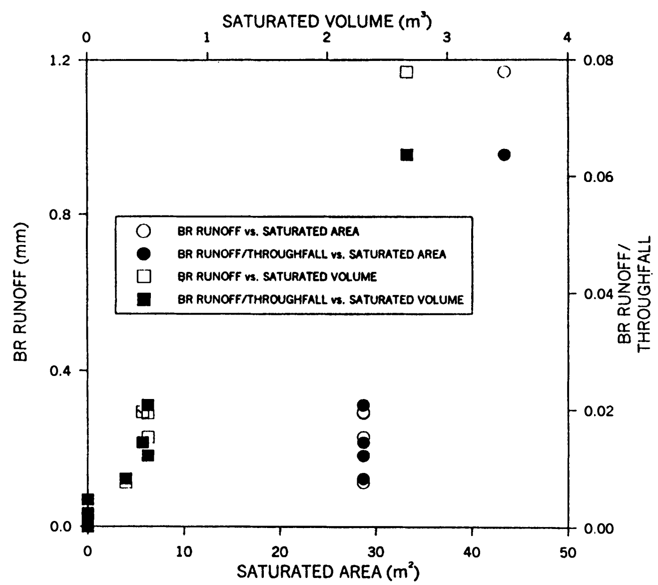

Fig. 8. *BR* runoff depth and runoff coefficient vs. estimated area and volume of saturated layer overlying the bedrock surface at the time of peak *BR* runoff.

layer was generally confined to a small area upslope of the trench face, and bedrock topography (Fig. 1) indicates that flow over the bedrock surface would be directed to this location. The saturated layer expanded upslope during larger, more intense events (*e.g.* YD 228), but never occupied more than a small fraction of the micro-catchment. Spatial and temporal properties of this saturated layer may be linked to the slope's ability to deliver flow at the soil-bedrock interface. Thus, *BR* runoff depth and runoff coefficient were strongly associated with the extent and particularly the volume of the saturated layer above the bedrock surface at the time of peak *BR* runoff (Fig. 8). Increased thickness and upslope extent may allow the saturated layer to receive flow contributions from a greater number of vertical macropores on the slope. This in turn would enable a greater fraction of throughfall to leave the slope quickly as *BR* runoff.

Conclusions

Hydrometric observations provided insight into the nature of throughfall partitioning on and within a forested hillslope typical of a substantial portion of the Canadian Shield landscape in south-central Ontario. A small fraction of incident throughfall was directed over and through the organic mat overlying the mineral soil. Runoff depths and runoff coefficients increased with throughfall intensity, but decreased with pre-event soil wetness. This suggests that throughfall moves vertically through the organic layer to the underlying mineral soil under wet antecedent conditions, rather than flowing laterally downslope. Hillslope soils exhibited vertical bypassing flow, and throughfall inputs appeared to reach the base of the profile via macropore flow while the near-surface soil matrix was gradually wetting up. Occurrence of macropore flow was directly related to throughfall intensity; however, results did not support the hypothesis that such bypassing flow is greatest under large θ conditions in the soil matrix when lateral water abstractions from the macropore would be minimized (Beven and Germann 1982). Independence of macropore flow and soil antecedent wetness implies that hydrophobic linings of macropore walls may have played a role in reducing lateral water abstractions from macropores to the surrounding matrix, and this process deserves further study. Subsurface flow measured above the soil-bedrock interface was also independent of pre-event soil water depth, although the strong association between *BR* runoff and peak throughfall intensity supported the hypothesis that runoff generation on the slope was controlled by coupled vertical and lateral macropore flow. The degree of macropore coupling and consequent efficiency in translating throughfall into subsurface flow appears to be related to the upslope extent and thickness of a saturated layer overlying the soil-bedrock interface. Comparison with previous studies on the slope suggests that greater antecedent wetness conditions and larger water inputs enhance the effectiveness of translatory flow as a runoff-generating mechanism. Implications of such shifts in the relative importance of runoff processes in response to changes in antecedent conditions and input properties must be considered when modelling the hydrological behaviour of forest slopes and in interpreting their hydrochemical response to throughfall inputs.

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