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Stormflow generation involving pipe flow in a zero-order basin of Peninsular Malaysia

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Abstract:

Hydrological responses in a zero-order basin (ZOB), a portion of whose discharge emerged via preferential flow through soil pipes, were examined over a 2-year period in Peninsular Malaysia to elucidate primary stormflow generation processes. Silicon (Si) and specific conductance (EC) in various runoff components were also measured to identify their sources. ZOB flow response was dependent on antecedent precipitation amount; runoff increased linearly with precipitation during events >20 mm in relatively wet antecedent moisture conditions. Runoff derived from direct precipitation falling onto saturated areas accounted for <0·2% of total ZOB flow volume during the study period, indicating the predominance of subsurface pathways in ZOB flow. ZOB flow (high EC and low Si) was distinct from perennial baseflow via bedrock seepage (low EC and high Si) 5 m downstream of the ZOB outlet. Pipe flow responded quickly to ZOB flow rate and was characterized by a threshold flow capacity unique to each pipe. Piezometric data and pipe flow records demonstrated that pipes located deeper in the soil initiated first, followed by those at shallower depths; initiation of pipe flow corresponded to shallow groundwater rise above the saprolite-soil interface. Chemical signatures of pipe flow were similar to each other and to the ZOB flow, suggesting that the sources were well-mixed soil-derived shallow groundwater. Based upon the volume of pipe flow during storms, the combined contribution of the pipes monitored accounted for 48% of total ZOB flow during the study period. Our results suggest that shallow groundwater, possibly facilitated by preferential flow accreted above the saprolite–soil interface, provides dominant stormflow, and that soil pipes play an important role in the rapid delivery of solute-rich water to the stream system.

KEY WORDS headwater; tropics; flow pathway; preferential flow; soil pipes; solutes; groundwater

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INTRODUCTION

Headwater areas are increasingly recognized as important components of the landscape providing sources of water, solutes, and sediments to downstream areas (Gomi *et al*., 2002). Owing to tight linkages between terrestrial and aquatic systems, activities within headwater catchments may result in immediate and conspicuous catchment responses, such as increases of sediment and nutrient export and alteration of hydrologic regimes (e.g. Campbell and Doeg, 1989). Nevertheless, these areas are continuing to be affected in most regions of the world, particularly in the tropics, where demands on land and natural resources are high (Bruijnzeel and Critchley, 1994; Thapa, 2001). Understanding of hydrological processes that affect solute and sediment movement within and from catchments is critical to identifying sensitive areas and promoting sustainable land use. In temperate regions, forest hydrologists and geomorphologists have elucidated various processes within headwater areas that suggest the relatively dynamic nature of hydrologic and mass wasting processes (Anderson and Burt, 1978; Dietrich and Dunne, 1978; Tsukamoto and Ohta, 1988; Montgomery, 1994; Sidle *et al*., 2000; Tsuboyama *et al*., 2000; Uchida *et al*., 2003). In the tropics, however, few studies have been conducted; thus, it is difficult to extrapolate the limited results to other areas (Bonnel and Gilmour, 1978; Elsenbeer *et al*., 1995a,b; Elsenbeer and Lack, 1996).

In forest soils of humid regions, various biophysical processes, including animal burrowing, development and decay of root systems, and periodic drying–wetting of soil, contribute to the formation of relatively large soil pores (Jones, 1971; Beven and Germann, 1982; Noguchi *et al*., 1997b, 1999). Connected forms of such pores provide preferential pathways (i.e. pipe flow), which transmit water rapidly compared with Darcian-controlled flow through the soil matrix (e.g. Beven and Germann, 1982; Mosley, 1982; Sidle *et al*., 2001). Numerous studies have demonstrated significant hydrological fluxes attributable to pipe flow during storms in forest soils of temperate regions (Mosley, 1979; Tsukamoto and Ohta, 1988; Wilson *et al*., 1990; Kitahara *et al*., 1994). In tropical regions, however, only a few studies have the examined roles of pipes in stormflow generation and delivery by continuously monitoring solute and water exports from

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individual pipes. For instance, Noguchi *et al.* (1997b) described the presence of connected soil pores by applying dye to the ground and related them to possible preferential flow pathways, and other studies measured flow rates and solute constituents of pipe flow (Walsh and Howells, 1988; Elsenbeer *et al.*, 1995a; Elsenbeer and Lack, 1996). Moreover, relatively little is known about the role of soil pipe flow related to solute delivery, and thus control of downstream runoff chemistry (see Luxmoore *et al.* (1990) and Elsenbeer *et al.* (1995a)).

Hydrological responses of a zero-order basin (ZOB) in a tropical rainforest of Peninsular Malaysia, a part of whose runoff drained as preferential pipe flow, were monitored. The objectives of this study were: (1) to determine dominant stormflow generation processes of the ZOB using both hydrometric and hydrochemical approaches; (2) to examine the specific mechanisms of pipe flow generation and the contribution of pipe flow to basin stormflow. Whether stormflow is generated by overland flow or through subsurface pathways affects stormflow chemistry considerably, owing to the varying contact times of water with solute-rich soil horizons relative to rainfall inputs (e.g. Mulholland, 1993; Elsenbeer and Lack, 1996). In particular, therefore, we attempted to quantify contributions of overland flow, i.e. infiltration-excess overland flow (Hortonian overland flow (HOF)) and saturation overland flow caused by direct precipitation onto saturated soil surfaces, relative to subsurface flow in stormflow generation.

METHODOLOGY

Site description

The study was conducted in a ZOB (1 ha; mean gradient 45%) of the Bukit Tarek Experimental Catchment 1 (BTEC1: 32·8 ha), located in Selangor Darul Ehsan, approximately 80 km northwest of Kuala Lumpur, Peninsular Malaysia (3°31′30″N, 101°35′E; Figure 1). Elevation of BTEC1 ranges from 50 to 180 m a.s.l., whereas the elevation of the ZOB spans from 70 to 130 m a.s.l. Daily air temperature measured at a nearby climate station ranges from 19 to 35 °C, with little interannual variation (Siti Aisah *et al.*, 2002). Average annual precipitation (plus/minus standard error) for the period 1991–2000 was 2803 ± 82 mm (Siti Aisah *et al.*, 2002); the monthly rainfall pattern typically shows a bimodal distribution, with peaks around May and November (Noguchi *et al.*, 1996). Surface geology consists of metamorphic sedimentary rocks, including quartzite, quartz mica schist, graphitic schist and phyllite from the Arenaceous Series (Saifuddin *et al.*, 1991). On a planar hillslope of BTEC1, depth to bedrock ranged between 118 and 571 cm (Noguchi *et al.*, 1997a). Representative forest species include *Koompassia malaccencis, Canarium* ssp., *Santiria* ssp., *Eugenia* spp., *Dipterocarpus crinitus, Dipterocarpus kunstleri*, and *Shorea leprosula*; non-commercial rattan and bamboo (e.g. *Gigantuchloa scortechinii*) are frequent on lower slopes and valleys. BTEC1 was selectively logged in the 1960s; its second-growth trees are now typically <30 m tall.

The lower portion of the ZOB was characterized by two concave slopes without incised perennial channels (Figure 1). An abandoned logging road (mean width of 3·4 m) crosses the mid-basin slope. During some of the heaviest storms in the wet season, we observed road runoff generated predominantly by the interception of subsurface flow (ISSF) from the road cutslope. All road runoff drained onto the lower slope within the ZOB at a conspicuous road runoff drainage node (RN) whose HOF contribution area was estimated to be 20 m^2 based upon preliminary field observation during several events (Figure 1). This exit point was likely a gully formed by historical existence of HOF from the road surface whose volume was much greater than HOF runoff observed during the study period. After occasional large storms, road runoff from the RN typically travelled along the valley bottom of the concave slope where return flow through several seepage points (including some definable soil pipes) emerged as overland flow forming a continuous overland flow line (Figure 1). However, such a flow line was discontinuous during smaller events because ISSF reinfiltrated along the valley bottom and also seepage return flow was not common. The outlet of the ZOB was characterized by a vertically exposed soil profile that provided a geomorphic break between the unchannelized ZOB valley and the perennial channel at the base of ZOB; a competent bedrock layer was exposed at the base of the 1·5 m of soil profile (Figure 1). Six soil pipes with outlet diameters >1 cm were found within the exposed profile at the channel head (Figure 1; Table I). ZOB runoff, therefore, contained a mixture of matrix and pipe flow from the soil profile that drained above the exposed bedrock, and any overland flow that originated further upslope. During non-storm periods in dry seasons, however, the ZOB became intermittent and baseflow of BTEC1 was provided by groundwater seepage emerging through bedrock fractures approximately 5 m downstream of the exposed soil profile (Figure 1).

A preliminary survey of soil physical characteristics and saturated hydraulic conductivity at several locations within the ZOB (see Figure 1) revealed a hydrologically impeding saprolite layer at a depth of ~1 m and an abrupt decrease in saturated hydraulic conductivity at the B_t–B_w horizon boundary (approximately 50 cm deep) occurred across the lower part of the ZOB (Ziegler *et al.*, 2006). Furthermore, shallow organic-rich soil of the ZOB was characterized by relatively high saturated hydraulic conductivity (10 cm depth; median of about 1000 mm h^{-1}) that greatly exceeded the prevailing rainfall intensity. Thus, we presume that storm flow generation due to HOF was negligible on hillslopes relative to other mechanisms, such as saturation overland flow or subsurface flow. Hereafter, saturation overland flow in this study refers to runoff generated from direct precipitation falling onto saturated ground surfaces (DPSA). Any return flow, including ISSF on the abandoned logging road, was treated as subsurface flow because this

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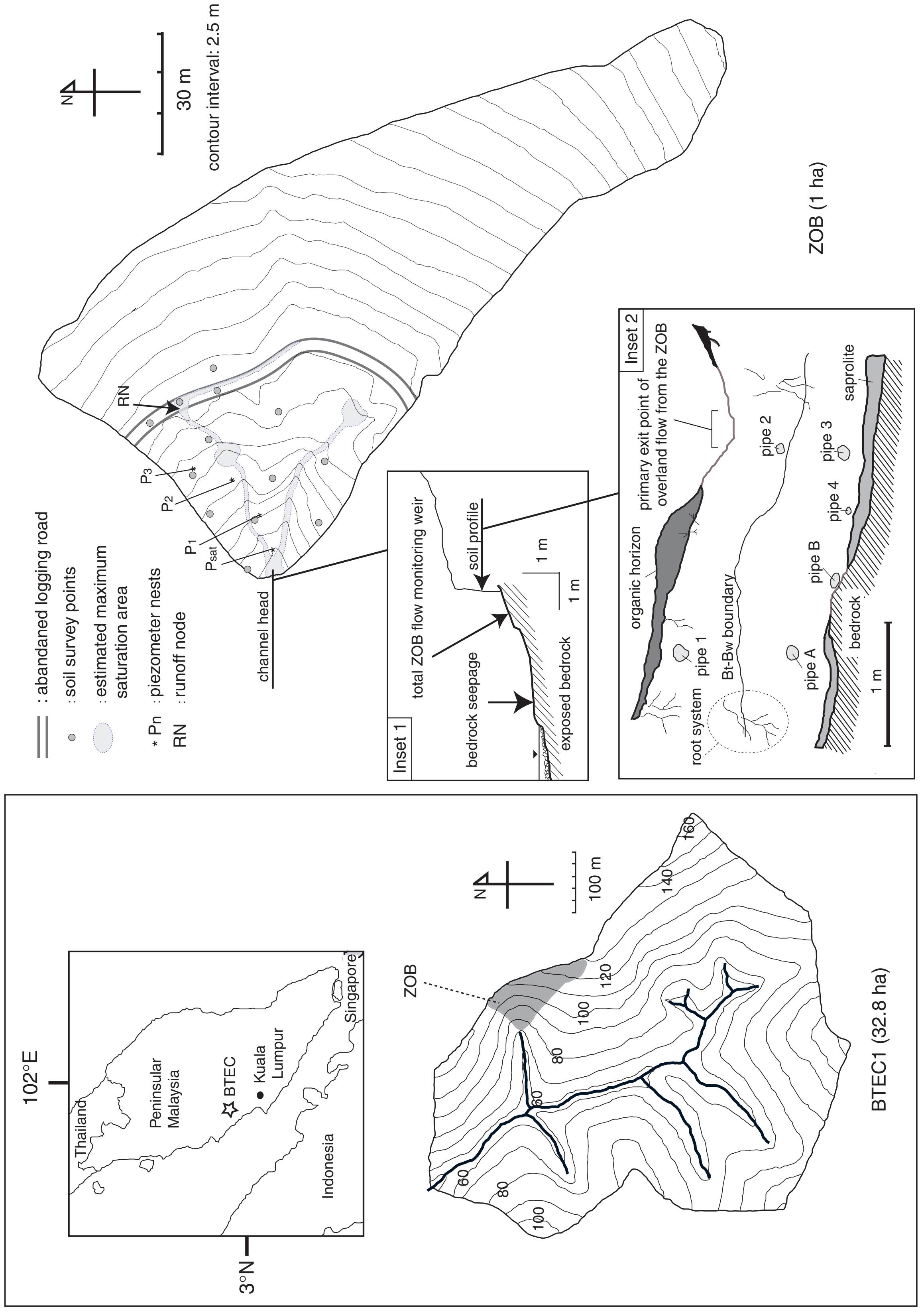

Figure 1. Map of Bukit Tarek Experimental Catchment 1 (BTEC1) and ZOB in Peninsular Malaysia. Inset 1 shows the outlet of the ZOB and locations of the ZOB weir and bedrock seepage; inset 2 illustrates the soil horizon at the outlet of the ZOB. Pipes A and B shown in the profile illustration were not examined in this study as they were hydrologically less active than the other four pipes of our interest

Table I. General characteristics of soil pipes, bedrock fracture, road runoff node, ZOB outlet[a]

Source name	Diameter A[b] (cm)	Size[c] (cm^2)	Length measured from outlet[d] (cm)	Maximum flow rate recorded ($l\ s^{-1}$)	Monitoring period
Pipe 1	7·5	33·2	80	3·4	May 2003–Nov 2004
Pipe 2	3·0	4·9	20	0·04	May 2003–Nov 2004
Pipe 3	4·3	13·5	20	1·4	May 2003–Nov 2004
Pipe 4	2·8	5·7	7	0·07	May 2003–May 2004
Pipe A	5·5	21·6	15	NA	NA
Pipe B	4·5	11·0	15	NA	NA
Bedrock fracture	NA	NA	NA	0·57	Apr–Nov 2004
Road runoff node	NA	NA	NA	>0·4[e]	May 2003–Nov 2004
ZOB	NA	NA	NA	36·4	Nov 2003–Nov 2004

[a] NA: not applicable.
[b] Diameter of pipes measured along the longest axis with a stick.
[c] Size of pipe calculated using the average of diameter A and another diameter measured perpendicular to diameter A.
[d] Length of pipes from outlet determined by inserting a straight solid stick.
[e] Flow rate of runoff node exceeded the capacity of the tipping bucket (i.e. 400 ml s^{-1}).

water had contact with the soil horizon before emerging on the surface.

Hydrometric approaches

Any flow draining from the ZOB above the exposed bedrock (total ZOB flow) was monitored during a 2-year period between 11 November 2002 and 10 November 2004. Additionally, flow from four pipes (pipe flow 1, 2, 3, and 4), a bedrock seep (BR flow), and overland flow from the RN were separately measured for varying periods (Table I). A PVC gutter cemented to exposed bedrock directed the total ZOB flow to a 60° v-notch weir. PVC pipes led pipe flows 1 and 3 to 60° v-notch weirs and pipe flow 2 to a tipping bucket (capacity of 31 ml); the outflows of these three pipes were then directed to the ZOB weir and measured as a part of total ZOB flow. Pipe flow 4 was directed using a PVC pipe to a tipping bucket (capacity of 400 ml) downstream of the ZOB weir due to limited space availability; flow rate of pipe 4 was included when calculating the total ZOB flow rate. Pipe outlets were maintained by fixing the PVC pipes to the soil pipe contact face with rapid-setting cement. The BR outlet was separated from other sources by diverting channel flow (i.e. total ZOB flow) using PVC sheeting and led to a 60° v-notch weir. The BR outlet was continuously wet throughout the monitoring period, making it impossible to apply cement. Thus, one end of a PVC pipe was cut to fit the surface topography of bedrock face around the BR outlet and attached as tightly as possible by filling the contact area with clay-rich subsoil material. Road runoff was monitored by cementing a galvanized zinc sheet into the node outlet; runoff was diverted to a tipping bucket of 400 ml capacity. The flow rate of weirs and the tipping buckets were monitored with water level sensors at 3 min intervals (WHR, TruTrack, NZ) and pulse data loggers (Onset, USA) respectively. Incident rainfall was monitored with a tipping-bucket rain gauge in one of two open areas approximately 450–550 m away from the ZOB. To minimize the effects of cements and zinc sheets on the chemical characteristics of water samples, hydrochemical monitoring was initiated at least 1 month after the instrumentations were completed; preliminary testing of solute levels above and below such materials did not show any detectable effects.

Three piezometer nests were installed in the ZOB (P_1, P_2 and P_3) to monitor development of hydraulic head relative to the ground surface (Figure 1). Each of the nests had two piezometers positioned 50 cm apart at depths corresponding to (1) the saprolite–soil interface (DP) and (2) the B_t–B_w horizon boundary (SP) determined by direct observation from auger holes (Table II). In addition, a single piezometer (P_{sat}) was installed 5 m upslope of the channel head soil profile at the depth of the saprolite–soil interface. Piezometers were constructed from 5-cm diameter PVC pipe, the lower perforated 20 cm of which was covered with 233 μm Nitex net to prevent sedimentation. Piezometer responses at 3 min intervals were monitored for varying periods of time using water level sensors (WHR, TruTrack, NZ; Table II).

Hydrochemical approaches

Both silicon concentration (Si) and specific conductance (EC) were used to distinguish primary sources of various runoff types and to elucidate dominant stormflow pathways. These parameters were chosen particularly because silicon in general serves as a good tracer of deep groundwater (e.g. Kennedy, 1971), and Zulkifli

Table II. General characteristics of piezometer nests; monitoring period April–September 2004

Piezometer nest	Piezometer depth (cm)		Duration of response	
	Shallow	Deep	Shallow	Deep
1 (P_1)	47	80	3·6 days	10·9 h
2 (P_2)	54	86	2·9 days	16·1 h
3 (P_3)	42	75	3·2 h	None

(1996) suggested that shallow throughflow was in general characterized by high EC among the other sources in BTEC1. Si and EC were measured in water samples collected from several locations at various times throughout the study period. Sampling locations included rainfall stations, piezometers (P_{sat} and P_1-DP), and various runoff outlets (ZOB flow, BR flow, and pipe flows). Rainfall samples were collected by bulk sampling via polyethylene funnels, piezometer samples were extracted using a hand pump, and runoff was collected as grab samples.

At least once every 2 months, these locations were sampled between 09 : 00 and 11 : 00 for periods when no storms occurred later than 24 : 00 of the previous day. However, variable sets of samples were obtained depending on different seasonal conditions (i.e. wet or dry seasons). The rainfall samples contained both the dry and wet deposition because the funnels were not rinsed before each storm event. For the purpose of this rather sporadic monitoring, BR was collected to characterize chemical signatures of groundwater only when the ZOB flow ceased during dry conditions. Thus, these samples were referred to as 'non-event period' samples. Additionally, these locations were intensively sampled during three consecutive events in November 2004 to characterize event-induced dynamic responses of chemical characteristics of discharge from the ZOB and pipes, as well as BR. For this event-based sampling, samples were collected from BR when total ZOB flow existed, thus allowing examinations of BR responses during storm events. Furthermore, EC in ZOB flow was monitored at 5 min intervals (YSI 6000 probe; Yellow Spring Incorporated, USA) and in BR outflow at 10 min intervals (Thermo Orion 635; Thermo Orion, USA). Water samples were immediately filtered through pre-ashed GF/F filters (pore size of 0·7 μm; Whatman, UK) on the same day of collection and split into two subsamples. One of the filtrates was immediately measured for specific conductance (YSI 63, Yellow Spring Incorporated, USA) and the other was analysed for silicon (ICP-OES, PerkinElmer, USA) within 2 weeks. Incident rainfall chemistry was based on the mean of the subsamples from the two rainfall gauging sites. As pipe 4 was measured outside the ZOB weir, the chemical characteristics of total ZOB flow excluded the influences of the pipe 4.

DATA ANALYSES

Zero-order basin flow separation

Rainfall events were defined as a 'storm' if at least 5 mm of precipitation was observed with no period for >60 min without rainfall. To examine storm-based runoff from the ZOB, the flow hydrograph was separated as follows:

- *Case 1* (see Figure 2a). When the ZOB had no flow at the storm onset and received no additional storm precipitation until flow ceased, all flow from the ZOB was considered to be stormflow.
- *Case 2* (see Figure 2b). When the ZOB had no flow at the storm onset but received additional storm precipitation after the 'event' ceased but before the flow ceased, we extended the 'event' falling limb downwards using the falling rate measured 0·5 to 1·5 h prior to the onset of the subsequent storm; thus, stormflow from the ZOB was assessed as all stormflow under the modified hydrograph (i.e. using the modified recession limb).
- *Case 3* (see Figure 2c). When flow occurred in the ZOB prior to an 'event' (i.e. contribution from a previous storm), the ZOB flow was determined as the area under the 'event' hydrograph after subtracting the extended hydrograph area for the preceding storm determined as in case 2.
- *Case 4* (see Figure 2d). When flow contributions occurred in the ZOB both from preceding events (as in case 3) and as rainfall after the storm 'event' but prior to the cessation of runoff (as in case 2), the ZOB flow was estimated by the combined methods described for the cases 2 and 3.

For cases 2, 3 and 4, separation procedures were limited to the storms whose inherent flow rates (B′) and those due to the preceding event (A′) decreased at least to 20% of their respective maximum peak flow rates (Bor A) (see Figure 2e). For these storms, the 7-day antecedent precipitation index (API_7) was calculated as an index of soil wetness (Mosley, 1982).

Saturation overland flow estimation

We used an indirect method to estimate soil surface saturation, and thus the contribution of saturation overland flow to total ZOB flow. Frequent field observations and preliminary examination of data from piezometers, rain gauges, and the ZOB weir indicated that ground surface saturation could occur during some large storms. When ISSF occurred at the road cut bank, road runoff drained from the RN together with seepage return flow developed ground saturation, particularly along the concave valley bottom slopes near the ZOB outlet (Figure 1). Occurrence of ISSF was easily detectable by a sudden increase of flow rate at the RN to the level that continuously exceeded the capacity of the tipping bucket (at a flow rate of >400 ml s^{-1} for a period >60 min). It was possible to gain a crude estimate of road-generated HOF runoff by assuming that any runoff at RN 30 min after the cessation of storm precipitation was caused by 100% ISSF; HOF runoff was calculated as hydrograph areas dissected by a line connecting the onset of runoff to the point at 30 min after the event cessation. Consequently, road-generated HOF that drained down through RN was only ∼15% of the rainfall input on the road surface area (20 m^2), constituting a minor contribution to catchment runoff. Small HOF road runoff was largely due to interception loss by vegetation and ponding and infiltration caused by the litter-rich surface. Furthermore, only when substantial ISSF input was measured at the RN, was the occurrence of surface saturation at P_{sat} (see Figure 1) indicated by

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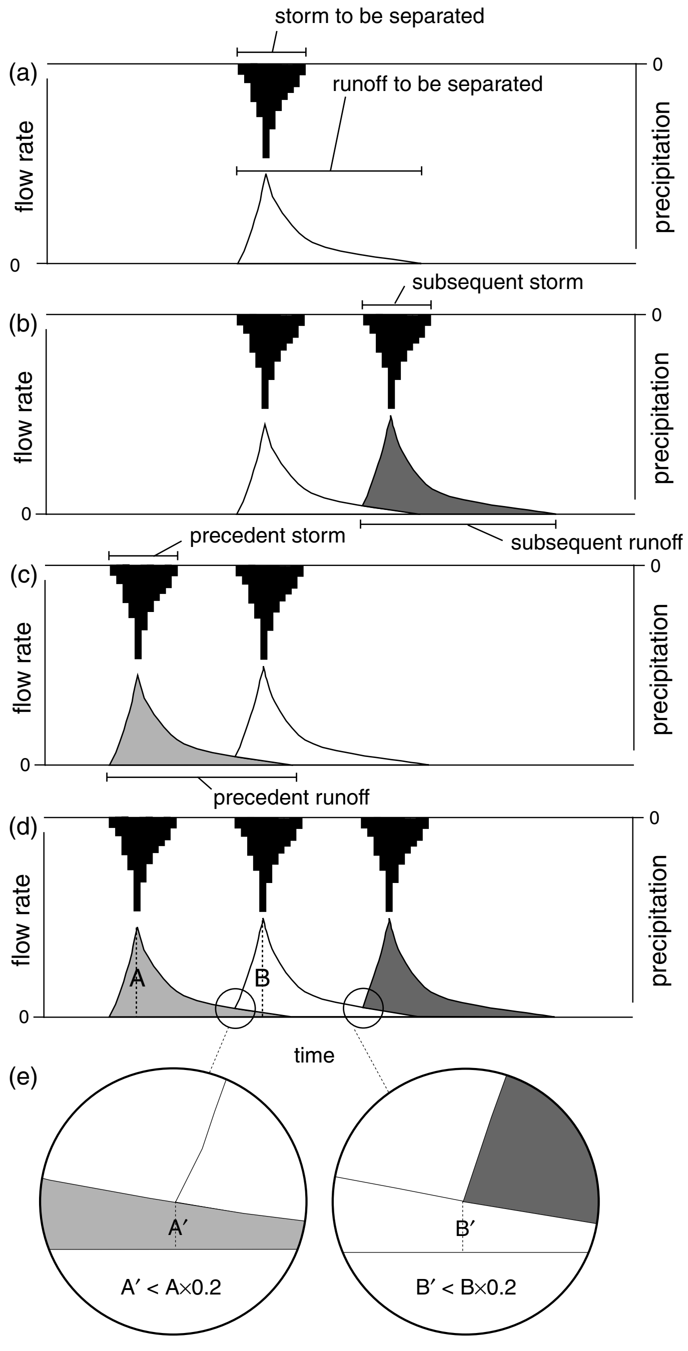

Figure 2. Schematic diagrams showing four cases of ZOB flow separation: (a) case 1, (b) case 2, (c) case 3, (d) case 4, and (e) shows hydrograph separation criteria for multi-event cases. See the text details about each of the cases

piezometric responses up to the ground surface, which was a prerequisite for the formation of saturation areas around the ZOB outlet. Consequently, we assumed that continuous ground surface saturation on the road, along the valley bottom, and in the relatively gentle areas near the centre of the concave slopes, which potentially contributed saturation overland flow to the ZOB outlet, only occurred for storms in which cutslope interception was observed. Maximum saturation areas were estimated by field observations after several intense storms augmented by evidence of conspicuously thinner litter layer due to return flow and overland runoff (i.e. 5 December 2002, 25 September 2003, and 7 October 2003). Using the liberal estimation of maximum saturation area (138 m^2; see the shaded area in Figure 1) and total rainfall accumulated after the initiation of road interception, we estimated the potential volume of saturation overland flow that contributed to the total ZOB flow.

Pipe flow responses and contribution

Event-based pipe contributions to the total ZOB runoff were estimated only for storms that met the following two conditions: (1) the total ZOB volume was successfully separated and (2) the flow measurement devices for all four pipes were functional. Pipe flow was separated using the same approach outlined for the ZOB flow separation.

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The relationships between the flow rate of each pipe and the total ZOB flow were established by obtaining best-fit regression models for the data available throughout the study period. These models were used to estimate pipe flow rate when direct measurements were not available either owing to malfunctioning or limited data storage capacity of monitoring instruments.

RESULTS

Zero-order basin flow responses

We observed a total of 242 storms during this study (11 November 2002–10 November 2004), for which the median storm precipitation and the median 10 min maximum rainfall intensity $I_{\max 10}$ were 17 mm and 45 mm h^{-1}, respectively (see Figure 3 for storm precipitation). Precipitation from storms accounted for 89% of the total precipitation (6287 mm). Hydrograph separation was applicable to 86 storms, representing 41% of the total storm precipitation (Figure 3). Runoff response was dependent on the API. The threshold precipitation for storm flow generation with $API_7 < 30$ mm and $API_7 \geq 30$ mm appeared to be 50 mm and 20 mm, respectively (Figure 3). Excluding the storms below these thresholds, linear regression models were fit to the total ZOB runoff y from the incident precipitation x for $API_7 \geq 30$ mm and <30 mm: $y = 0{\cdot}8316x - 19{\cdot}218$, $r^2 = 0{\cdot}95$, $p < 0{\cdot}001$ and $y = 0{\cdot}427x - 20{\cdot}665$, $r^2 = 0{\cdot}42$, $p < 0{\cdot}05$, respectively (Figure 3).

Contribution of saturation overland flow due to direct precipitation falling onto saturated ground surfaces

Conditions favourable for saturation overland flow generation occurred during seven relatively large storm events from the population to which we applied storm flow separation techniques (Figure 3; Table III). Despite this, we likely overestimated the saturation overland flow because of using potential maximum area rather than variable area; the contribution of saturation overland flow to the total ZOB runoff was negligibly small. Estimated runoff caused by saturation overland flow due to DPSA for these events ranged between 0 and 1·3 mm, comprising 0–0·12% of event-based total ZOB runoff (Table III). During the study period, no other storms exceeded the conservative thresholds for generation of saturation overland flow inferred during these events: thresholds were precipitation >73 mm, $I_{\max 10} > 69{\cdot}9$ mm h^{-1}, and $API_7 > 18{\cdot}3$ mm (see Table III).

Pipe flow responses and contribution

Examples of pipe flow responses are presented for three storms with varying precipitation, antecedent condition, and rainfall intensity on 7 October 2003 (86 mm precipitation, $API_7 = 32{\cdot}3$ mm, $I_{\max 10} = 110$ mm h^{-1}), 4 July 2004 (76 mm precipitation, $API_7 = 0$ mm, $I_{\max 10} = 104$ mm h^{-1}), and 31 August 2004 (25·4 mm precipitation, $API_7 = 6{\cdot}6$ mm, $I_{\max 10} = 25{\cdot}2$ mm h^{-1}). A relatively small storm on 31 August 2004 resulted in immediate responses of pipes 3 and 4; pipe 4 initiated first, followed by pipe 3; the combined contribution of pipe flow to the total ZOB flow ranged between 0 and 60% of total ZOB flow and its response corresponded

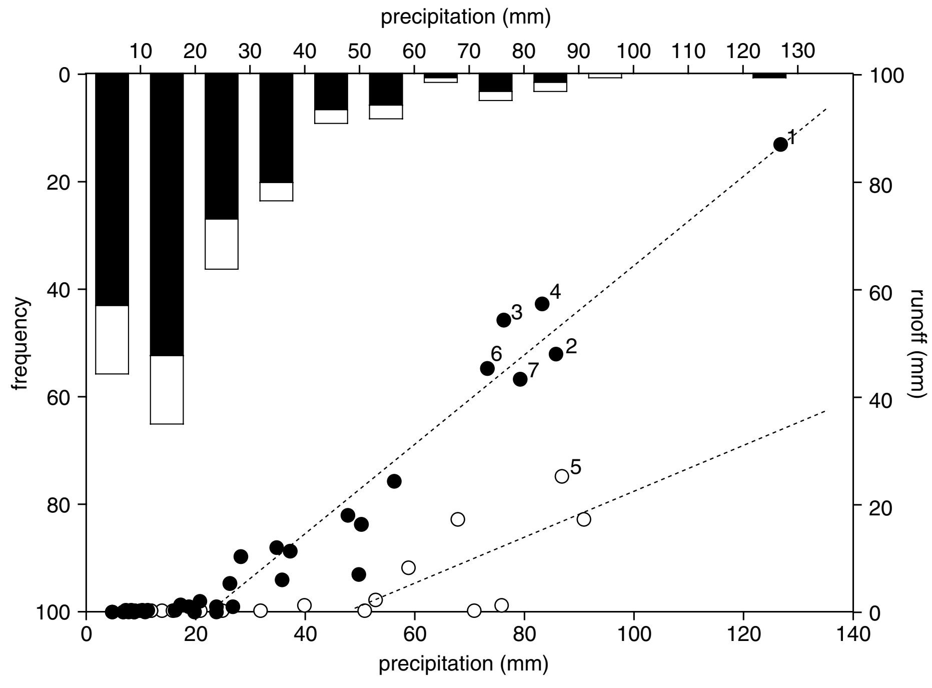

Figure 3. Frequency distribution (bars) and runoff responses (circles) of storm events observed between November 2002 and November 2004. Open circles and bars denote storms with $API_7 < 30$ mm; filled circles and bars correspond to storms with $API_7 \geq 30$ mm. Numbered storms are those during which interception of subsurface flow was observed at the road RN; more detailed information on these events is shown in Table III. Dotted lines indicate regression lines that significantly predicted runoff from incident precipitation; see the text for more details of hydrograph separation

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Table III. General characteristics of storms that recorded road interception of subsurface flow

Storm ID	Date	Total rainfall (mm)	Duration (min)	$I_{max\,10}$ (mm h^{-1})	API$_7$ (mm)	Estimated SOF[a] (mm)
1	2 May 2003	126·8	389	148·8	69·9	1·27
2	7 Oct 2003	85·5	234	109·8	32·3	0·62
3	2 Nov 2003	73·0	343	69·9	93·5	0
4	9 Nov 2003	76·2	218	76·9	179	0·06
5	12 Nov 2003	82·5	232	111·8	192	0·46
6	29 Apr 2004	86·5	120	141·8	18·3	0·06
7	5 Nov 2004	79·2	127	101·8	148	0·16

[a] SOF: saturation overland flow.

well to that of total ZOB flow (Figure 4). During this event, P_{sat} did not register any responses. A larger storm with dry antecedent conditions on 4 July 2004 resulted in responses from all pipes; flow initiation in pipes 3 and 4 was earlier than in pipes 1 and 2. The combined contribution of pipe flow to the total ZOB ranged between 0 and 60% and pipe discharge corresponded closely to the total ZOB flow rate (Figure 5). However, the timing of

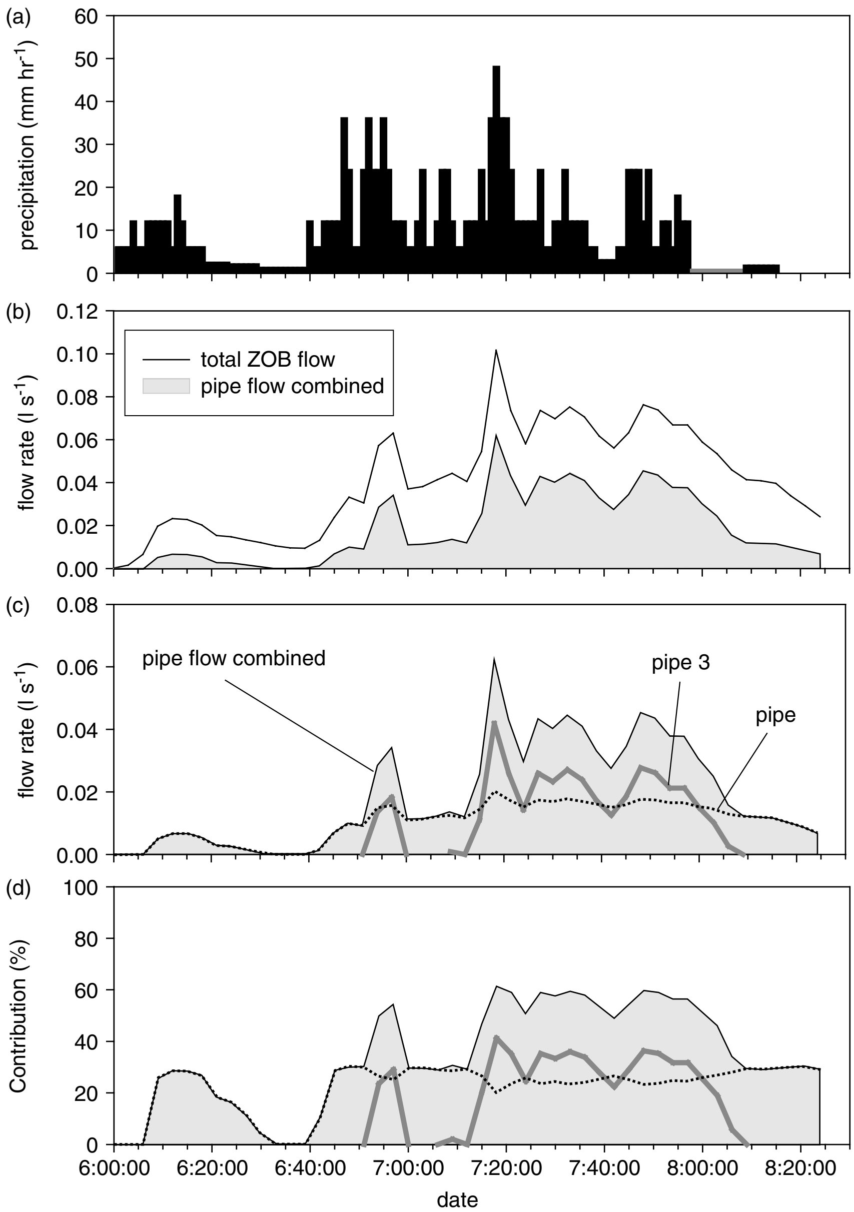

Figure 4. (a) Precipitation, (b) responses of total ZOB flow and combined pipe flow, (c) responses of individual pipes, and (d) contribution of pipe flow during the event on 31 August 2004 (25·4 mm precipitation, $API_7 = 6·6$ mm, $I_{max\,10} = 25·2$ mm h^{-1}). Note that the legend of (d) is as (c)

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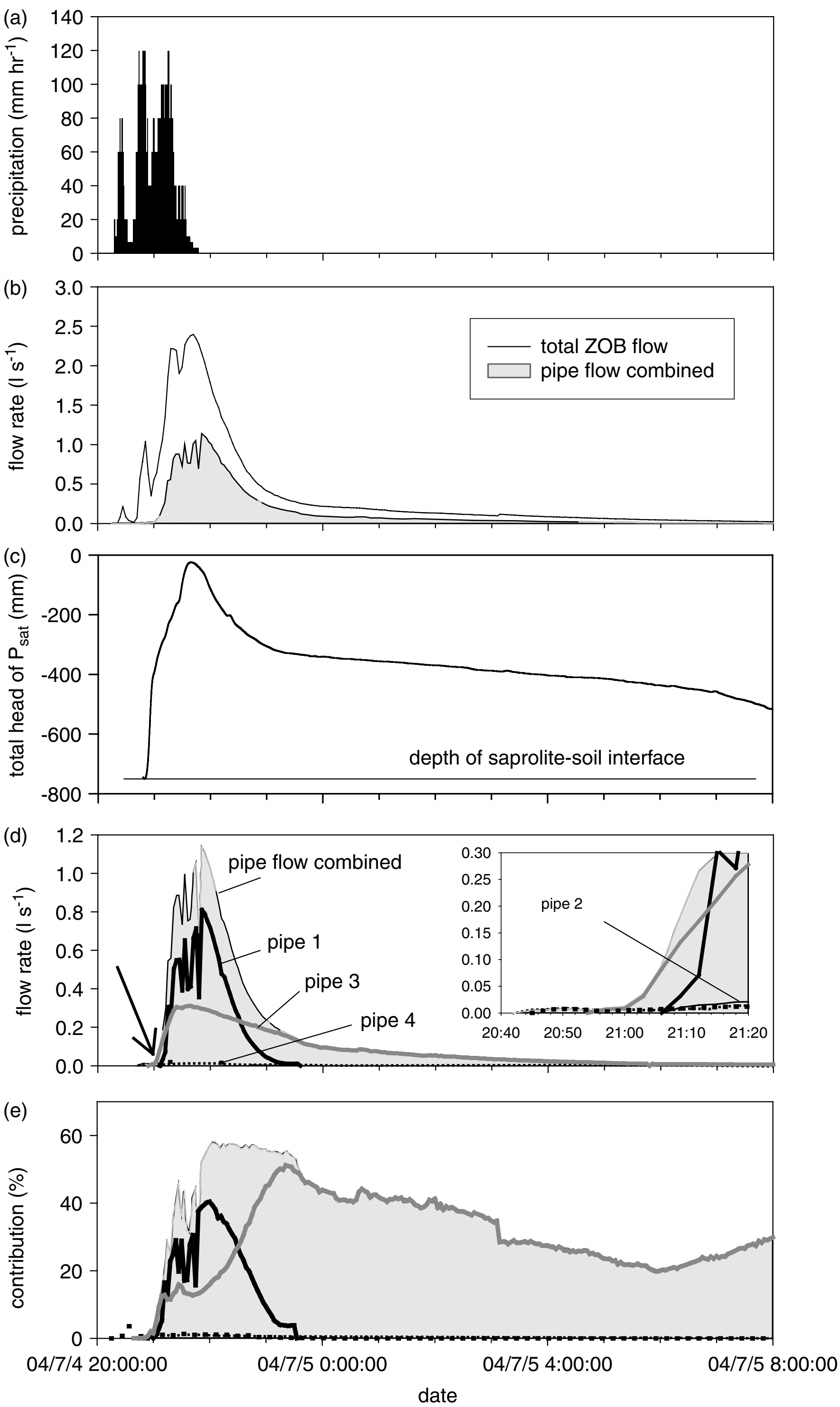

Figure 5. (a) Precipitation, (b) responses of total ZOB flow and combined pipe flow, (c) response of total head of P_{sat}, (d) responses of individual pipes, and (e) contribution of pipe flow during the event on 4 July 2004 (76 mm precipitation, $API_7 = 0$ mm, $I_{max\,10} = 104$ mm h^{-1}). Note that the legend of (e) is as (d). The inset in (d) shows an enlargement of the initial flow response denoted by the arrow

the larger discharge from pipe 1 corresponded to a relatively low contribution from the other pipes (Figure 5e). During this event, P_{sat} indicated the development of a hydraulic head near to the ground surface (Figure 5c). The similarly large storm on 7 October 2003 with high antecedent rainfall condition resulted in a discharge from all four pipes; flow initiated from pipes 3 and 4 earlier than from pipes 1 and 2; the contribution of the four pipes to the total ZOB flow ranged between 0 and 70%; however, in this case, the contribution of combined pipe flow decreased considerably when the total ZOB discharge was high (Figure 6). During this event, P_{sat} indicated the development of a hydraulic head to the ground surface (Figure 6c). Thorough examination of other events showed that pipe flow generally initiated from the two lower pipes followed by those at higher

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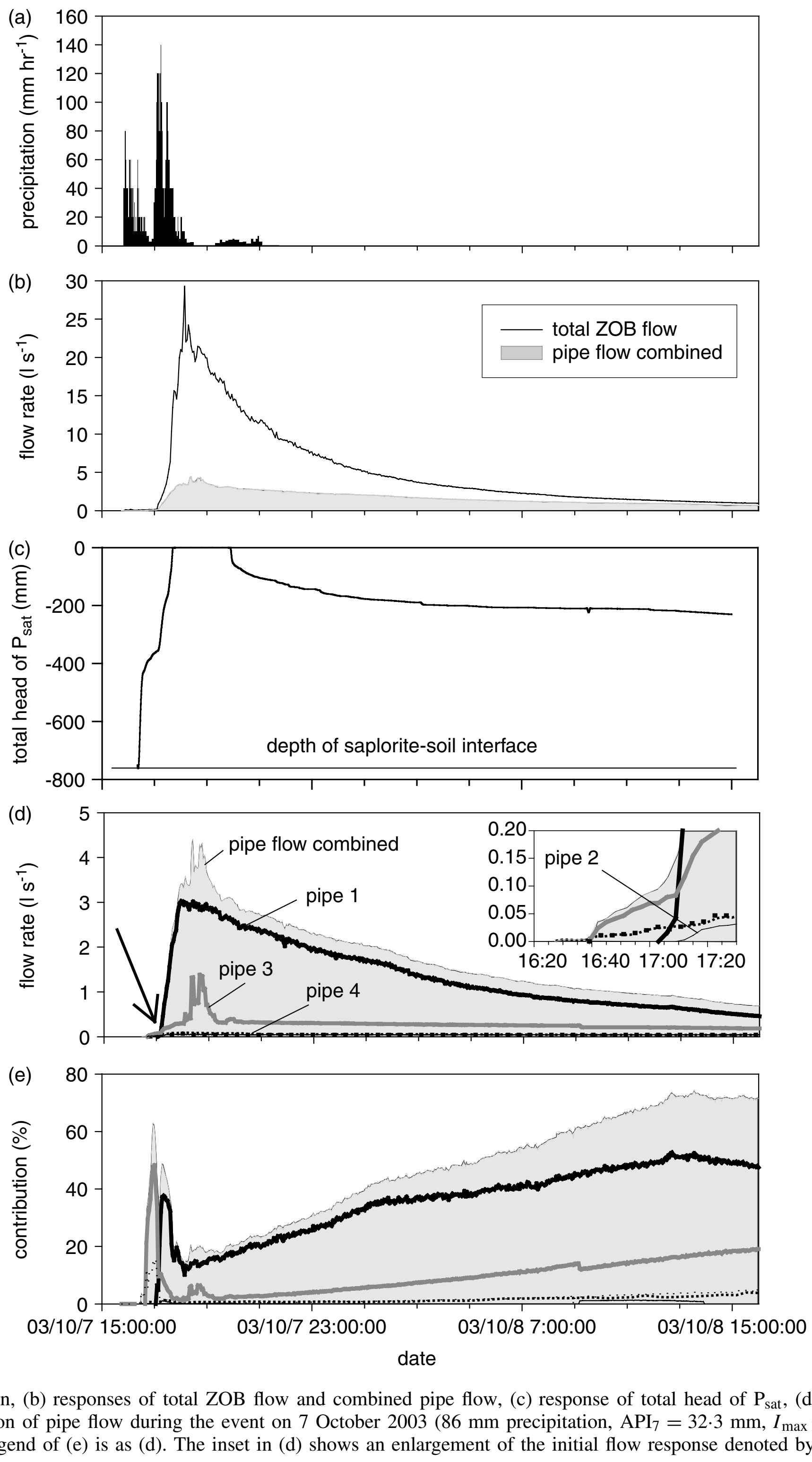

Figure 6. (a) Precipitation, (b) responses of total ZOB flow and combined pipe flow, (c) response of total head of P_{sat}, (d) responses of individual pipes, and (e) contribution of pipe flow during the event on 7 October 2003 (86 mm precipitation, $API_7 = 32{\cdot}3$ mm, $I_{max\,10} = 110$ mm h^{-1}). Note that the legend of (e) is as (d). The inset in (d) shows an enlargement of the initial flow response denoted by the arrow

positions within the soil horizon. Furthermore, discharge from pipes 1 and 2 occurred less frequently than from the other two pipes. In general, large storms were required to initiate discharge from the pipes positioned higher within the horizon. Nevertheless, when flow did occur from pipe 1 (uppermost location), it completely dominated the total pipe discharge.

Within the range of the total ZOB flow rates observed during the study period (i.e. maximum of 33 l s^{-1}), the maximum flow rates were attained for pipe 1 (2·8 l s^{-1}), followed by pipe 3 (0·3 l s^{-1}), pipe 4 (0·07 l s^{-1}) and pipe 2 (0·03 l s^{-1}); this order was related to the sizes of the pipe outlets (see Table I). Observed pipe flow rates were significantly fit to the observed total ZOB flow rates by logarithmic regressions (Figure 7a and Table IV). Pipes were characterized with varying initiation discharges and rates of increase against total ZOB flow. Initiation was earliest for pipe 4, followed by

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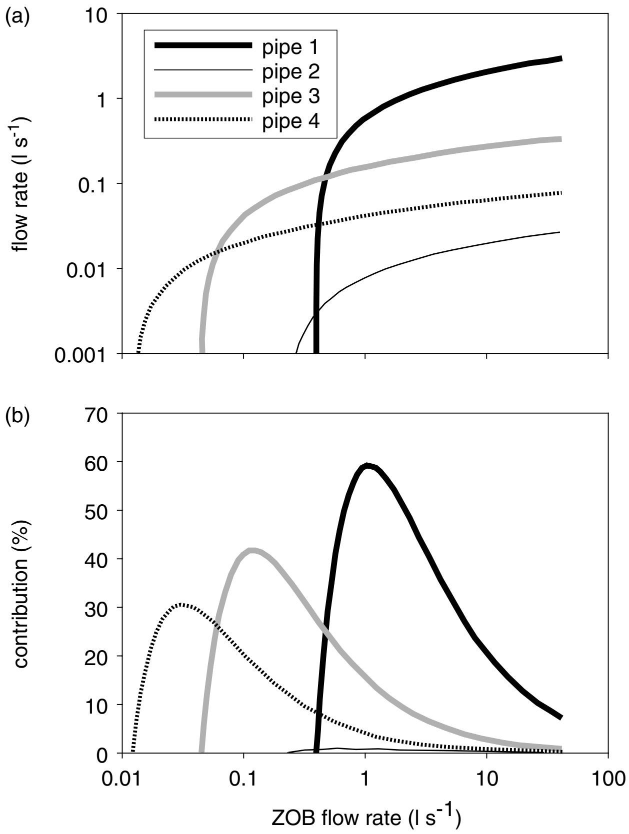

Figure 7. (a) Logarithmic models that relate total ZOB flow rate to flow rate of individual pipes, which were derived from monitoring of pipe flow rate during the study period; see Table IV for the model details. (b) Contribution of individual pipes to total ZOB flow rate. Note that *x*-axes on both panels and *y*-axis in (a) are logarithmic scales

Table IV. Regression models that predict instantaneous pipe flow rate *y* from ZOB flow rate *x*

Pipe	Regression	R^2	P
1	$y = 0{\cdot}63\ln(x) + 0{\cdot}59$	0·88	<0·01
2	$y = 0{\cdot}0052\ln(x) + 0{\cdot}0078$	0·45	<0·05
3	$y = 0{\cdot}05\ln(x) + 0{\cdot}15$	0·79	<0·01
4	$y = 0{\cdot}093\ln(x) + 0{\cdot}04$	0·74	<0·01

pipes 3, 2, and 1. Flow from each pipe appeared to reach a threshold value, after which little increase was observed with further increase in total ZOB flow. Conversion of individual pipe discharge to a proportional contribution to the ZOB flow showed that each pipe responded uniquely (Figure 7b); maximum contributions to total ZOB flow were 60%, 43%, 31%, and 2% for pipes 1, 3, 4, and 2 respectively.

Event-based contributions of pipes to total ZOB runoff were successfully obtained for a total of 49 storm events. For these 49 events, only a small fraction of pipe flow rate had to be estimated using the regression models shown in Figure 7a; percentages of estimated pipe flow for pipes 4, 3, 2 and 1 were 90, 98, 86 and 98, respectively. Contributions of pipes were variable and depended upon storm precipitation, and these patterns differed among the pipes (Figure 8). The combined contribution of the four pipes characterized by a polynomial model ranged from 20 to 60%, with the peak contribution to total storm precipitation of approximately 50 mm (Figure 8a). The contributions of pipes 1 and 2 were both characterized by polynomial models, with their maximum contributions occurring during the events with total precipitation >60 mm (Figure 8b and c). In contrast, contributions from pipes 3 and 4 were best described by exponential decay curves, with their greatest contributions occurring for the storms of precipitation <30 mm (Figure 8d and e).

Piezometric responses

The deeper piezometer response was much more frequent than that of the shallow piezometers (Table II and Figure 9). For most cases, no hydraulic head occurred in the shallow piezometers (P_1 and P_2) until the deeper piezometers responded to approximately the depth of the shallow piezometers; subsequent increases in piezometric heads for both deep and shallow piezometers were similar (Figure 9). Greater total head in the shallow piezometer relative to the deep piezometer was observed during the early stages of a few intense storms (i.e. 29 April and 4 July 2004) and a storm (6 July 2004) that occurred 2 h after a 22 mm storm (Figure 9). Such responses suggest infrequent occurrences of perched water tables, and thus possible lateral throughflow at the B_t–B_w boundary. In contrast, the shallow piezometer never responded in nest 3.

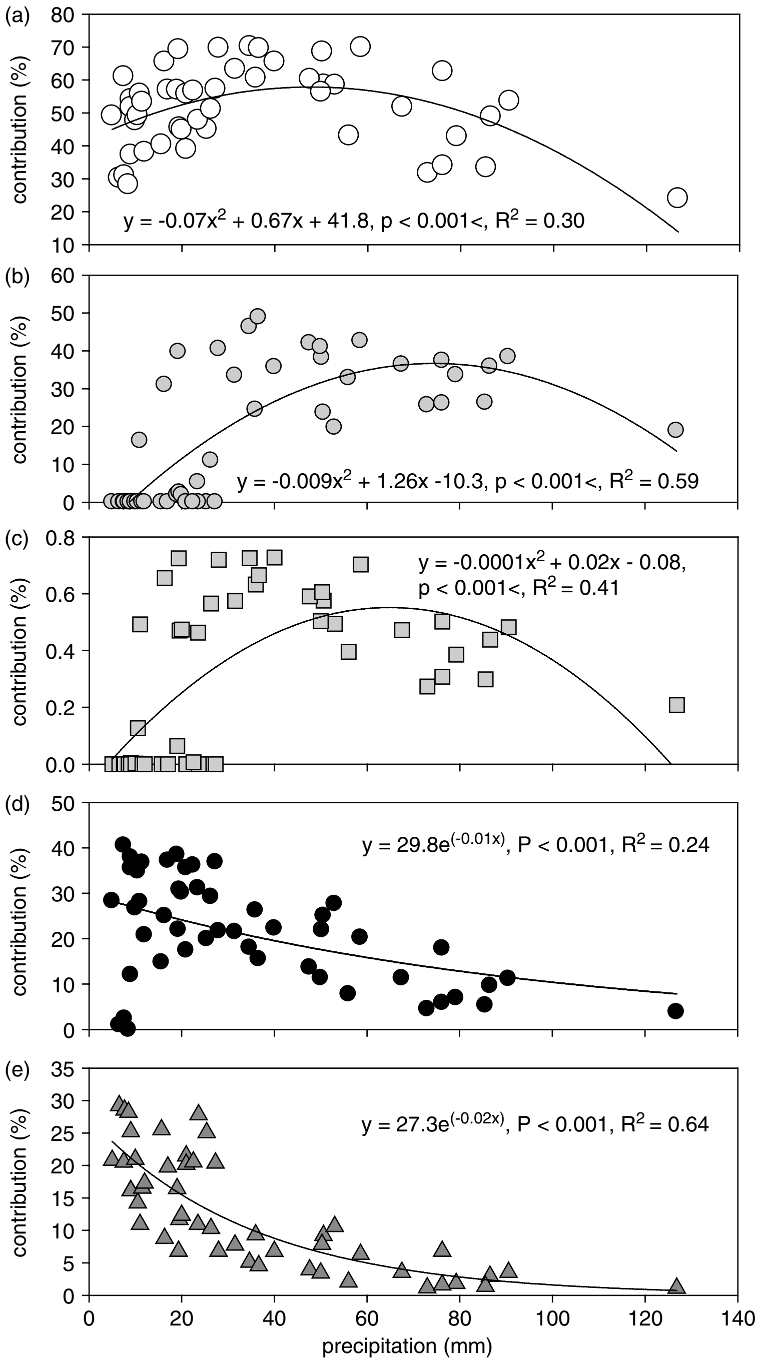

Figure 8. Event-based contributions of (a) four pipes combined, (b) pipe 1, (c) pipe 2, (d) pipe 3, and (e) pipe 4. Note that the relationships in (a), (b) and (c) are polynomial models; the relationships in (d) and (e) are exponential decay models

Sporadic measurements of rainfall, runoff, and saturated soil water

Silicon and specific conductance were significantly different among various sources (i.e. incident rainfall, BR flow, pipe flow, and extracts from the piezometers; Figure 10: $p < 0{\cdot}001$ for both variables with one-way ANOVA). Silicon concentration was highest in BR flow and lowest in the incident rainfall; other locations had intermediate levels of silicon. Specific conductance was lowest for incident rainfall and highest for pipes, total ZOB flow and piezometer samples; BR discharge had an intermediate value.

Intensive event monitoring of rainfall, runoff, and saturated soil water

Flow from pipes and BR responded immediately to rainfall (Figure 11). BR flow recession after storms was more abrupt than recession discharge from pipes. Specific conductance of BR flow was much lower than that of the other sources measured at the ZOB outlet before events. During events, the specific conductance of BR flow increased proportional to flow, but it was still lower than that of pipe and ZOB flow. Total ZOB flow exhibited pulses of reduced specific conductance (regions B in Figure 11d) that matched the pattern

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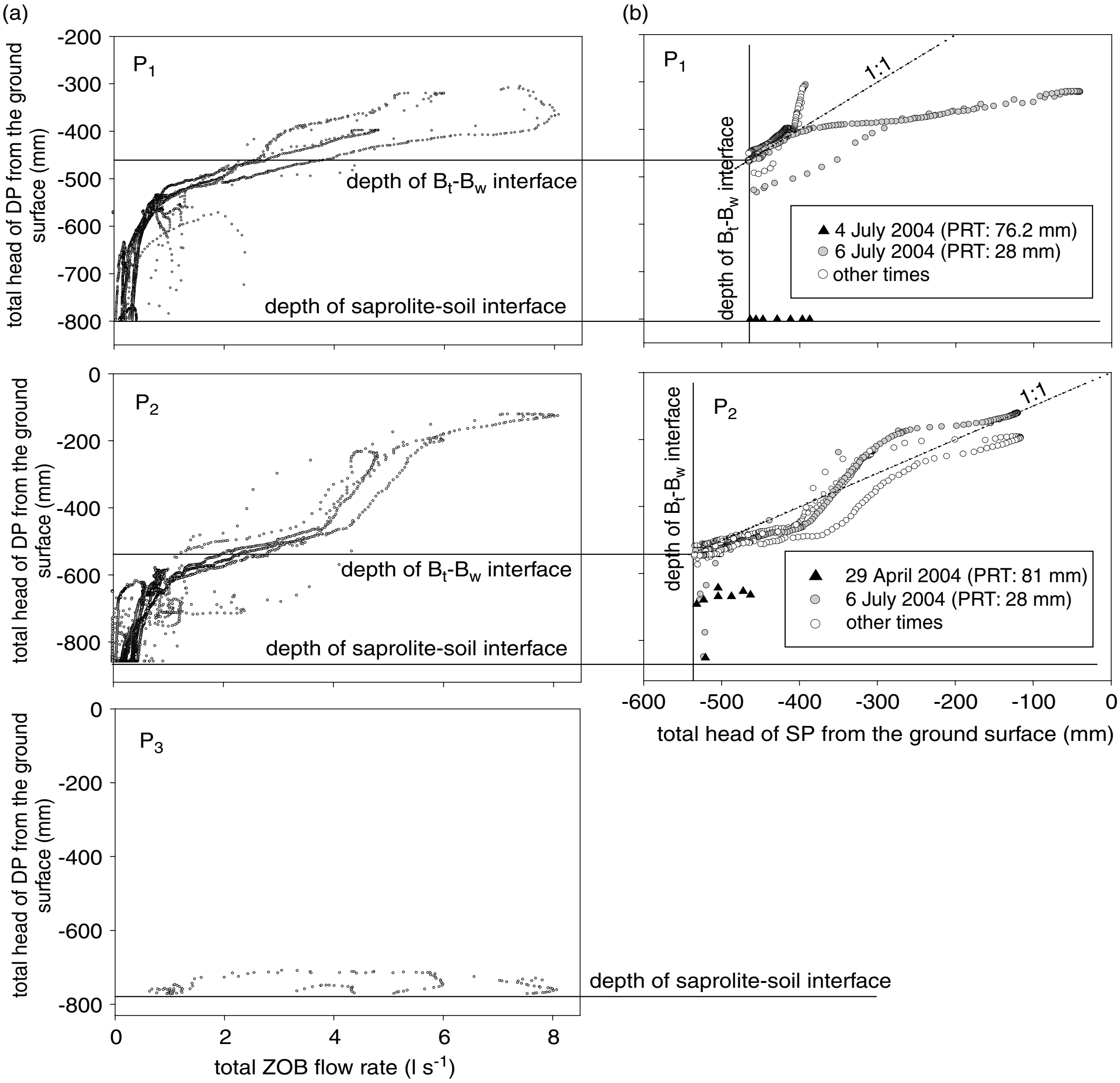

Figure 9. (a) Responses of deep piezometers relative to total ZOB flow. (b) Responses of SP relative to deep piezometer (DP); dotted 1 : 1 lines predict the relationship between SP and DP when responses of SP are caused by rising of saturated zone detected by DP. PRT is event precipitation

of incident rainfall; rainfall had the lowest specific conductance of all sources. Shortly after peak flows, specific conductance of total ZOB discharge was higher than the pre-event values (regions A in Figure 11d). Specific conductance of all pipe flow was similar and was indistinguishable from total ZOB flow, except the relatively low value for pipe 2 (Figure 11d). Silicon concentration was lowest for rainfall, highest for BR discharge, and intermediate for both total ZOB flow and pipe flow (Figure 11e). Unexpectedly low levels of both specific conductance and silicon concentrations in pipe 2 samples were apparently caused by the influence of event water due to its proximity to the valley bottom (see Figure 1).

DISCUSSION

Elucidation of stormflow generation processes has long been a central issue in hydrogeomorphology. This is because it forms the basis for developing process-based models of runoff generation, transport of materials (i.e. nutrient, pollutants, and sediment), and landform evolution. Although such knowledge could provide critical insights into spatially explicit predictions of the effects of land use activities on catchment processes, few attempts have been made in tropical environments. Our findings demonstrated that subsurface flow pathways provided the dominant stormflow pathway in the ZOB of Peninsular Malaysia. In particular, the hydrologically impeding saprolite–soil interface played a role in the accretion of solute-rich shallow groundwater. Furthermore, active pipe flow appeared to be connected to the sources above the saprolite–soil interface, with different sets of soil pipes providing efficient drainage depending on the precipitation amount.

The dominant contribution of saturation overland flow caused by DPSA was emphasized in early studies on stormflow generation in gently sloping temperate regions

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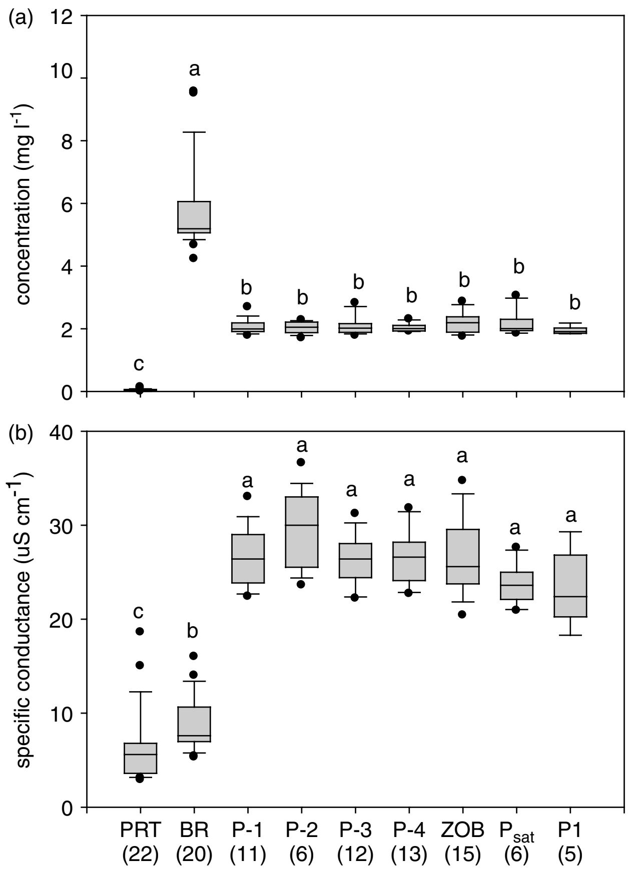

Figure 10. Silicon concentration and specific conductance of various sources measured in 'non-event period' monitoring. P-1, P-2, P-3, and P-4 denote pipes 1, 2, 3, and 4 respectively; PRT is event precipitation. Numbers in parentheses beside source ID denote sample size. Letters above bars indicate the results of Tukey's multiple comparison following one-way analyses of variance (ANOVAs) that were separately conducted for the two variables; data points accompanied by different letters are statistically different

(e.g. Dunne and Black, 1970). Subsequent studies in generally steeper (more incised) topography demonstrated the predominance of subsurface flow in hydrograph formation (e.g. Mosley, 1979; Pearce *et al.*, 1986; Tsukamoto and Ohta, 1988; Wilson *et al.*, 1990; Sidle *et al.*, 1995). Mechanisms of subsurface drainage sufficiently rapid to augment storm hydrographs have been partly explained by the existence of preferential flux via soil pipes (e.g. Mosley, 1979, 1982; Tsukamoto and Ohta, 1988; Kitahara *et al.*, 1994; Uchida *et al.*, 1999). On the other hand, the literature on stormflow generation processes in humid tropical regions underscores the importance of limited infiltration capacity at shallow depth relative to ambient rainfall intensity and resultant dominance of overland flow generated on saturated surfaces or as return flow originating from shallow soil horizons. For example, stormflow generation was explained by extensive saturation of the surface 20 cm of soil and DPSA-driven overland flow in South Creek in tropical Australia (Bonnel and Gilmour, 1978; Elsenbeer *et al.*, 1995b). Elsenbeer and Lack (1996) provided information on a western Amazonian catchment where subsurface return flow from the surface 10 cm constituted the major portion of the storm hydrograph (see also Elsenbeer and Cassel, 1990; Elsenbeer *et al.*, 1995a).

Interactions amongst various soil properties, geomorphic features, and rainfall characteristics determine the predominant hydrological pathways in stormflow generation (e.g. Freeze, 1972; Tsukamoto and Ohta, 1988; Sidle *et al.*, 2000). The catchments in South Creek, Australia, and western Amazonia were both characterized as conducive to overland flow generation; below a shallow soil horizon (~10–20 cm) the saturated hydraulic conductivity decreased abruptly (Bonnel and Gilmour, 1978; Elsenbeer and Cassel, 1990; Elsenbeer *et al.*, 1995a). In contrast, soil was deeper in our basin (i.e. ~1 m deep), with a hydrologically impeding saprolite layer occurring beneath the soil. Despite the very low saturated hydraulic conductivity (i.e. <2 mm h^{-1}) below the B_t–B_w transition (Ziegler *et al.*, 2006), the development of a perched water table at this depth was not the dominant influence on runoff generation, perhaps due to the existence of a spatially heterogeneous preferential flow network that allowed vertical percolation and lateral transport of precipitation input (see Noguchi *et al.* (1997b, 1999) and Sidle *et al.* (2001)). A possible explanation for the observed phenomenon is that vertical and lateral preferential flow pathways may facilitate the observed accretion of a saturated zone at the saprolite–soil interface (as evidenced by piezometric measurements), thus contributing to this subsurface flow mechanism. Nevertheless, such subsurface water accretion rarely reached the ground surface. This indicated the overriding importance of subsurface flow pathways, strongly influenced by preferential flow via pipe 1, relative to saturation overland flow caused by DPSA.

Sources of subsurface runoff can be classified into those originating from deep groundwater sources and those deriving from saturated soil zones within a relatively shallow soil zone above hydrologically impeding layers. Because these different pathways generally differ in residence time and contact materials, the chemical signatures of the solutes also tend to differ (e.g. Mulholland, 1993). In our study, the ZOB flow (including flow from pipes) was considerably different, both in EC and silicon, from the BR discharge that provided baseflow during rather dry periods (Figure 10). Zulkifli (1996) related the EC of stream water to concentrations of solutes (such as nitrate and potassium) that originated from shallow, organic-rich soil horizons in BTEC1. Furthermore, the concentration of silicon tends to be high in deep groundwater sources (Kennedy, 1971). Therefore, the chemical signatures of the ZOB flow (high EC and low silicon) and BR (low EC and high silicon) are consistent with the view that the primary source of ZOB flow is saturated soil water above the saprolite–soil interface. Recent studies have emphasized the hydrological interaction of vadose and bedrock zones and preferential pathways through bedrock fractures (e.g. Anderson *et al.*, 1997; Montgomery *et al.*, 1997). Furthermore, Uchida *et al.* (2002, 2003) suggest that deep groundwater recharge may occur during stormflow near the outlet of unchannelled

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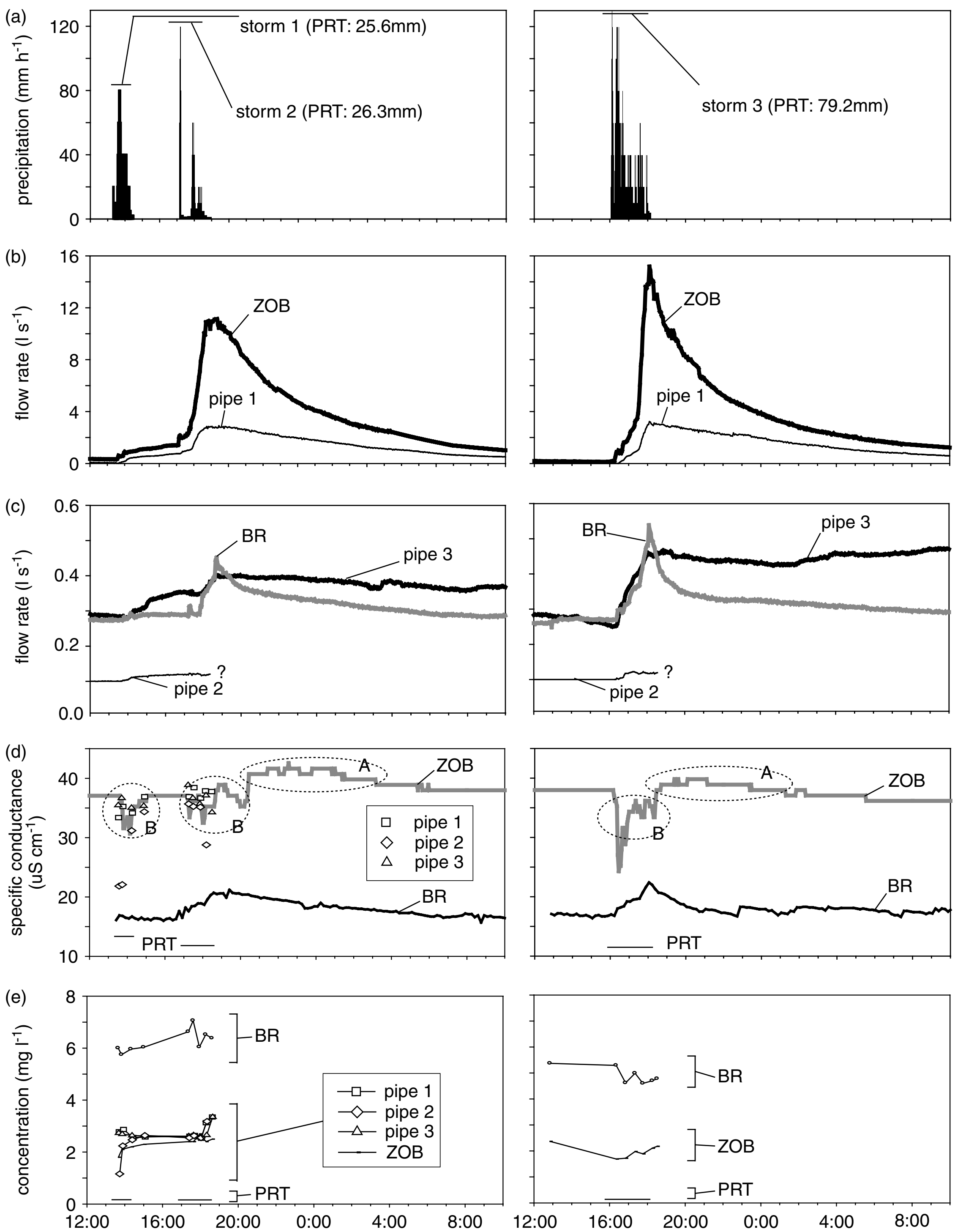

Figure 11. (a) Precipitation, (b) flow rate of the ZOB and pipe 1, (c) flow rate of pipes 2 and 3 and BR, (d) specific conductance, and (e) silicon concentration from various sources (ZOB, soil pipes, and bedrock (BR)) for three storms in November 2004. PRT is event precipitation. Note that data for pipe 4 are not shown because monitoring was terminated in May 2004. Missing flow response of pipe 2 was caused by shortage of data storage in monitoring instruments

basins based on relatively higher silica concentration and colder water temperature relative to those expected for shallow groundwater. Our sporadic measurements of silicon and EC taken from piezometers showed no difference between two locations, one near the ZOB outlet and the other approximately 15 m up-slope (Figures 1 and 10) during several storms in 2003 and 2004. More importantly, BR discharge had a pronounced influx of solute-rich shallow groundwater with EC high during events (Figure 11d). Also, a reduced specific conductance of the ZOB discharge during events (Figure 11d) was apparently caused by the influx of event water. Therefore, these results suggest that the ZOB flow that we monitored mostly contained hydrological fluxes derived from the zone above the soil–saprolite interface. Furthermore, interactions between soil and saprolite–bedrock

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zones was mostly the gradual percolation of the portion of water that built up above the soil–saprolite interface to deeper bedrock sources, perhaps through saprolite and bedrock fractures rather than the recharge of water from deep groundwater sources mixing with water within soil zone.

Applying the polynomial model in Figure 7a to the other storm events during the study period, 48% of the total hydrological flux from the ZOB was drained through these four pipes. Based upon field observations, the reduced contribution of pipes to the ZOB discharge during relatively large storms (see also Figures 6e and 7b) was caused by both the threshold flow capacity shown for each pipe (Figure 7a) and the increase of the total ZOB flow largely due to return flow that emerged via soil pipes (diameter >1 cm) and more diffuse seepage along the valley bottom axis of the basin. Such expansion of source areas of subsurface flow that are rapidly converted to overland flow most likely caused the increase of EC shortly after the peaks in the November 2004 storms owing to flush-out of solutes (regions A in Figure 11d). Thus, the total contribution of soil pipes to subsurface drainage and runoff is greater than our estimates, at least supporting the significance of preferential flow as a major stormflow component (Mosley, 1979; Tsukamoto and Ohta, 1988; Wilson *et al*., 1990; Kitahara *et al*., 1994). In our catchment, Noguchi *et al*. (1997b) inferred that the primary causes of pipe development are biological activities, such as decayed roots and termite nests in shallow soil horizons. Although the exact origin of the pipes we studied is unknown, their development may have been initiated by such biological activities. The most elusive attribute of soil pipes is perhaps the spatial extent and connectivity of the pipe network, and their source areas (e.g. Jones, 1971; Beven and Germann, 1982; Sidle *et al*., 2001). In our case, development of shallow groundwater and progressive initiation of pipes 3 and 4 (outlets in a deeper horizon) followed by pipes 1 and 2 (outlets at a shallower horizon) (Figures 4–7) are consistent with the view that their source areas are located at different depths within the soil profiles. Unfortunately, our research design did not allow us to elucidate spatially explicit characteristics of the pipe network. The similarity of the chemical signatures of the pipes and of two piezometers (Figure 10) at least supports one of the working hypotheses, namely that the spatial extent of these pipe networks is limited to the area near the outlet of the ZOB and piezometers, but substantially facilitates the efficient drainage of well-mixed shallow groundwater that builds up above the soil–saprolite interface within such an area.

Earlier studies in BTEC1 reported consistent increases in specific conductance of stream water during events with high precipitation and wet antecedent conditions (Zulkifli, 1996; Sammori *et al*., 2004). This phenomenon is also observed in the monitoring of water quality conducted in parallel to the present study (Negishi, 2006). Furthermore, Zulkifli (1996) related such increases in specific conductance to stormflow that originated from the shallow soil horizon. In contrast, Noguchi *et al*. (1997a) found little evidence of substantial hydrological flux through the shallow soil horizon on a relatively planar hillslope, having failed to provide plausible explanations of rapid stormflow generation in BTEC1 that occurred during storms with precipitation >20 mm and relatively high antecedent soil moisture. The findings from our investigation reconcile most of the confusion generated in these previous reports. Our hydrological monitoring of the ZOB runoff clearly shows that thresholds of stormflow generation are sensitive to antecedent soil moisture contents (see Sidle *et al*. (1995, 2000)), which almost matched the reported thresholds for BTEC1 response (Noguchi *et al*. 1997a; Negishi, 2006). Furthermore, sporadic 'non-event period' and intensive event-based monitoring of hydrochemical data demonstrated that the ZOB stormflow was characterized by the highest specific conductance amongst the other sources and was apparently caused by contact with the shallow soil horizons. Therefore, ZOBs are likely the geomorphic units that become the dominant stormflow contributor, at least during moderate to large storms. These observations concur with earlier findings that convergent slopes exhibit more dynamic hydrological behaviour than planar slopes (e.g. Dunne and Black, 1970; Anderson and Burt, 1978; Sidle *et al*., 2000). Our results, furthermore, suggest that the convergent hillslopes, such as ZOBs, are not only more hydrologically dynamic, but also contribute disproportionately to solute export relative to planar hillslopes within the catchment.

CONCLUSIONS

Our results demonstrate the dominant role of subsurface flow pathways during stormflow generation in a zero-order forest basin in Peninsular Malaysia. Moreover, our hydrometric and hydrochemical data suggest that stormflow was largely provided by solute-rich, soil-derived shallow groundwater perched above the saprolite–soil interface. Soil pipes were estimated to have contributed approximately 50% of total ZOB flow during the study period, suggesting an important contribution in draining solute-rich stormflow to downstream systems. It is conceivable that such efficient drainage facilitated by preferential flow networks reduces the chance of extensive surface saturation, thus exporting soil-derived solutes rather than highly diluted water to downstream systems. In concurrence with the previous studies, our study underscores the uniqueness and dynamic nature of ZOBs relative to planar hillslopes. Although studies in the tropics that involve monitoring of catchment response are increasing (e.g. Abdul Rahim and Harding, 1992; Malmer and Grip, 1994; Zulkifli, 1996; Noguchi *et al*., 1997a), knowledge regarding intra-catchment processes is very limited. Careful attention should be paid to the intrinsic heterogeneity of hydrological processes within headwater catchments when tropical forest sites are managed. This study suggests that any modifications of hydrological pathways in

ZOBs may result not only in the alteration of hydrological regimes and/or sediment export, but also in severe disruption of the nutrient cycles in catchments, at least in the areas that share similar lithology, climate, and flow generation processes to our study area.

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