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Catena 67 (2006) 89 – 104
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Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in Peninsular Malaysia

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Received 20 July 2005; received in revised form 27 January 2006; accepted 23 February 2006

Abstract

Using a constant-head permeameter we found an abrupt natural decrease in saturated hydraulic conductivity (K_s) within the upper 1.0-m soil profile of an Orthoxic Tropudult at the Bukit Tarek Experimental Catchments research area in tropical, Peninsular Malaysia. The depth at which low K_s could cause a perched water table in response to high-intensity rainfall, however, was too great to generate saturation overland flow on planar hillslopes in the study area. The effects of logging activity on K_s at five subsurface depths (0.1, 0.25, 0.5, 0.75, and 1.0 m) on the non-roaded portion of the harvest area were examined at the three following sites, which differed in the degree of disturbance and recovery since timber harvesting: (1) selective logging conducted in the 1960s; (2) mechanized selective tree removal conducted 4 years ago; and (3) high-impact clear-cutting just prior to measurement. This recent logging greatly disturbed the soil surface (via compaction, topsoil/subsoil mixing, burning) and produced comparatively high variability in near-surface K_s. Changes in K_s at or below 0.25-m, however, were not detected with certainty at any sites. In terms of hillslope hydrologic response, the connectivity of zones of low K_s in the harvest area with dense networks of skid trails and terraces was identified as one of the most important consequences of timber harvesting, although this phenomenon was not quantified. We estimate the recovery time for near-surface K_s on the non-roaded hillslope to be less than 40 years.

Keywords: Soil depth; Saturated hydraulic conductivity; Perched water table; Rainfall intensity; Runoff generation; Logging impact recovery; Skid trails; Ultisol; Amoozemeter; Knocking-pole penetrometer

1. Introduction

Hydrological and geomorphological impacts associated with forest disturbance in moist tropical watersheds have been reported (cf. Bruijnzeel, 1993; Douglas, 1999; Sidle et al., 2006). When extensive mineral soil is exposed, surface erosion and the delivery of sediment and nutrients to the stream can be accelerated (Douglas et al., 1992; Baharuddin and Abdul Rahim, 1994; Malmer, 1996). Evidence worldwide suggests that changes in interception loss, evapotranspiration, infiltration, and stormflow pathways caused by various degrees of forest conversion can alter the timing and magnitude of basin baseflow and storm discharge for an unpredictable period of time (cf. Harr et al., 1975; Bosch and Hewlett, 1982; Bruijnzeel, 1990, Beschta et al., 2000; Bruijnzeel, 2004; Guillemette et al., 2005). Logging roads and skid trails in particular can alter hydrologic response and serve as sediment sources and transport pathways on cleared lands (Megahan and Kidd, 1972; Reid and Dunne, 1984; Swift, 1988; Bruijnzeel and Critchley, 1994; Ziegler and Giambelluca, 1997; Croke et al., 1999; Wemple et al., 2001; Chappell et al., 2004a).

Field studies assessing impacts of logging and/or forest conversion in tropical areas often look at runoff and

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0341-8162/$ - see front matter
doi:10.1016/j.catena.2006.02.008

sediment yields from experimental catchments or monitored plots (e.g., Baharuddin, 1983; Rijsdijk and Bruijnzeel, 1991; Douglas et al., 1992; Abdul Rahim and Harding, 1992; Brooks et al., 1994; Malmer, 1996; Adbul Rahim, 1998; Douglas, 1999; Hartanto et al., 2003; Chappell et al., 2004a). Another common assessment approach is quantifying changes in surface physical properties, such as infiltrability, bulk density, porosity, or organic material (e.g., Malmer and Grip, 1990; Kamaruzaman and Muhamad Majid, 1992; Brooks and Spencer, 1997). Some studies have investigated changes in hydrological variables within the soil profile that would have implications for the partitioning and movement of subsurface stormflow (e.g., Van der Plas and Bruijnzeel, 1993; Malmer, 1996; Noguchi et al., 1997a; Godsey and Elsenbeer, 2002; Ziegler et al., 2004; Zimmermann et al., 2006). Collectively, prior research demonstrates that management practices in tropical forests *do* alter water/sediment yield and delivery mechanisms, but to varying degrees (Bruijnzeel, 1990; Douglas, 1999; Bruijnzeel, 2004; Chappell et al., 2004b). While the realm of hydrologic changes associated with logging roads can be appreciated through comparison with numerous prior studies conducted world-wide (reviews by Gucinski et al., 2000; Luce, 2002), a thorough understanding of logging-related changes to stormflow pathways on the non-roaded portions of harvested hillslopes, however, is more elusive.

In this work we investigated depth-related changes in saturated hydraulic conductivity (K_s) on hillslope soils in a managed tropical forest in peninsular Malaysia. The objective was to ascertain how the differing types of logging activities have affected permeability within the soil profile. By doing so, we hoped to improve our understanding of how stormflow pathways may have been affected by disturbance and how these effects have recovered over time.

2. Study site

2.1. Physical description

The study was conducted at the Bukit Tarek Experimental Catchments (BTEC) research facility, which is located within Compartment 41 of Bukit Tarek Tambahan Forest Reserve (Fig. 1). The site is in Selangor Darul Ehsan (Sulaiman et al., 1991), approximately 60 km NW of Kuala Lumpur, in Peninsular Malaysia (3° 31′30″ N, 101° 35′E). Elevation ranges from 40 to 100 m asl. Annual rainfall is approximately 2400 mm (Noguchi et al., 1996), falling during two principal monsoon seasons: April–May and October–November. The average annual rain day total is 150 days (Sulaiman et al., 1991). During the period 1992–1994, Noguchi et al. (1996) found that November was the

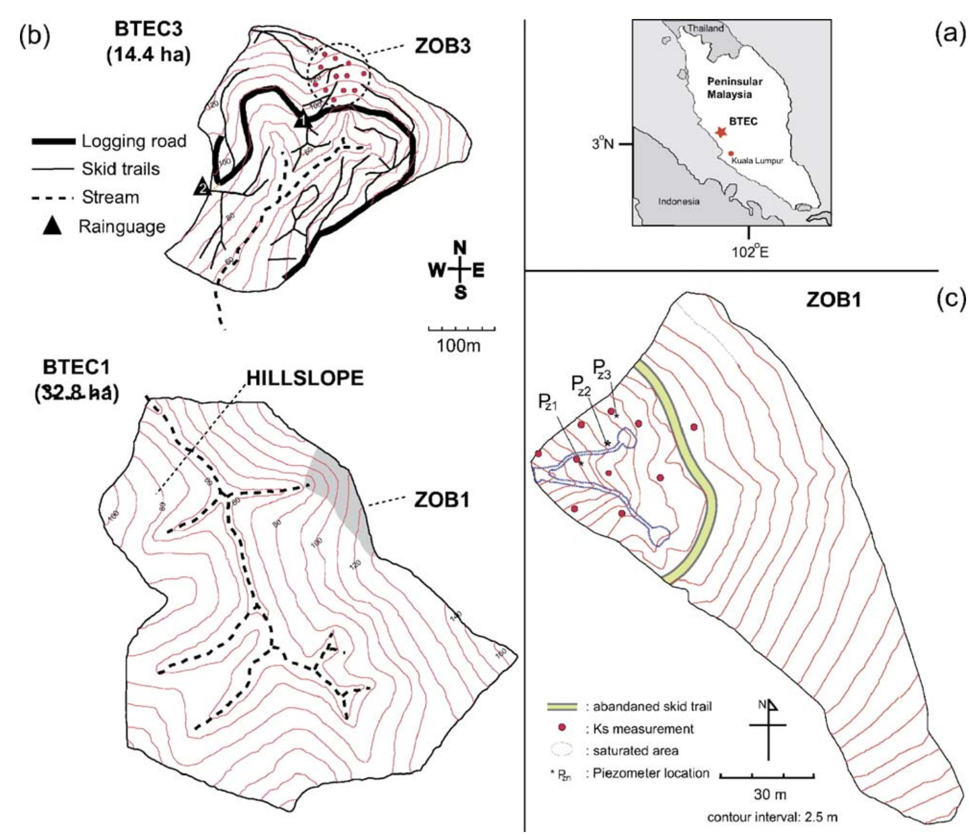

Fig. 1. (a) Bukit Tarek Experimental Catchments research site in peninsular Malaysia; (b) general locations of HILLSLOPE, ZOB1, and ZOB3 measurement areas in BTEC; the numerals for the rainfall gauges indicate changing the measurement location prior to logging in 2003; (c) K_s measurement locations and positions of the three piezometer nests in ZOB1.

wettest month (350 mm); and January, the driest (<110 mm). Vegetation resembles the *Kelat-Kendondong* forest type described by Wyatt-Smith (1963); note others have called this *Kempas-Kendondong* (Sulaiman et al., 1991).

Two principal soil series are found in Bukit Tarek: *Kuala Brang* (Orthoxic Tropudult) and *Bungor* (Typic Paleudult). The former occupies 90% of the area; the latter 10% typically occurs at lower elevations (cf. Sulaiman et al., 1991; Zulkifli et al., 2000). These soils are derived from arenaceous rocks and argillaceous sediments that were deposited during the Triassic Period (Roe, 1951; Sulaiman et al., 1991). A low-grade metamorphism converted the arenaceous deposits into quartzite, quartz mica schist, and schistose grit; the argillaceous sediments were changed to mica schist and indurated shale.

2.2. Measurement sites

BTEC is situated on stateland property that was logged in the early 1960s before becoming a forest reserve area (Sulaiman et al., 1991). Controlled logging activities within BTEC has created a suitable venue for numerous recent hydrogeomorphic studies (Zulkifli, 1996; Noguchi et al., 1996, 1997a,b; Sidle et al., 2004; Sammori et al., 2004; Negishi et al., 2006, in press). Observations in catchments experiencing differing types of management–and therefore various levels of disturbance–suggest differences in types of runoff generation mechanisms may be related directly to specific logging impacts. Rapid stream flow response to rainfall at these sites, for example, suggests the wide-spread occurrence of Hortonian overland flow (rainfall rate in excess of infiltrability and ponding, Horton, 1933) on roads and skid trails in particular, but perhaps also on compacted/exposed soils on harvested hillslopes—although this latter process has not been documented. Water exfiltrating from road cutbanks is another active runoff process (Sidle et al., 2004).

We conducted the K_s measurements in experimental catchments BTEC1 (32.8 ha) and BTEC3 (14.4 ha). The following four "treatments" were investigated (Fig. 1):

- *ZOB1* — A 1.0-ha zero-order basin in BTEC1 that was selectively logged for high-value trees in the 1960s. To facilitate logging, a low-density network of skid trails was constructed with a bulldozer. The trails were abandoned following logging, allowing them to recover naturally. Second-growth trees are now typically <30 m tall on non-roaded hillslopes.
- *HILLSLOPE* — A 200-m hillslope in BTEC1 with a relative relief of about 60 m. Maximum gradient approaches 1 m m^{-1}; and the hillslope extends from the stream channel to interfluve. High-value trees were

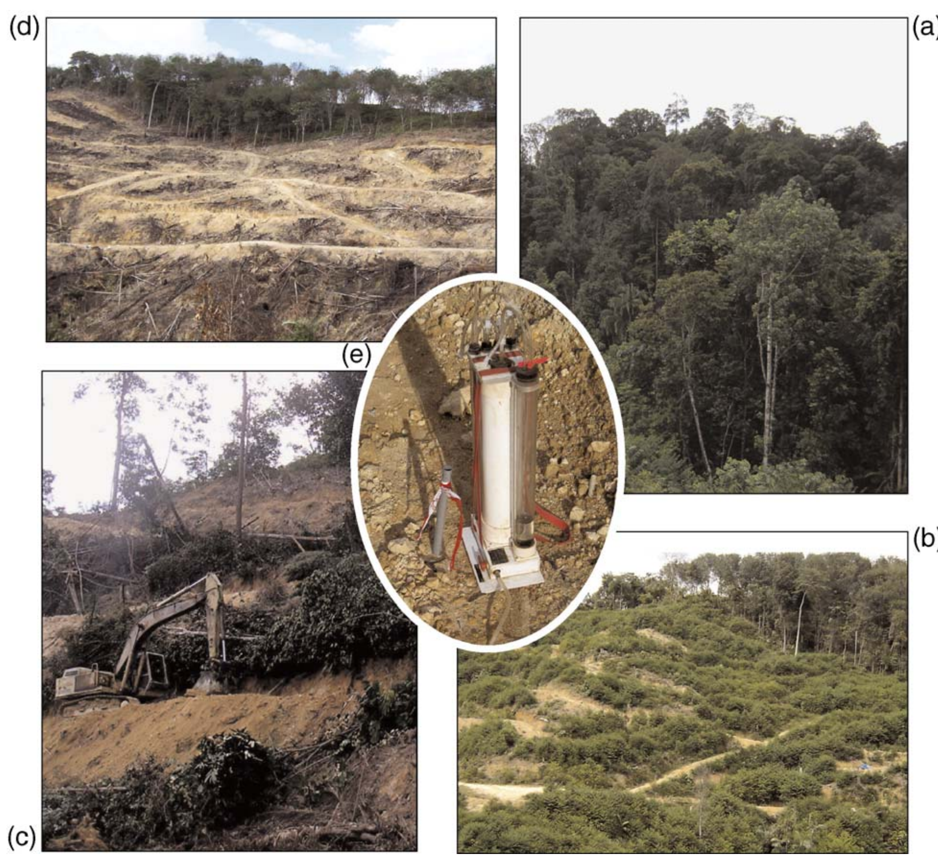

Fig. 2. (a) *Kelet-Kendondong* forest in BTEC; (b) vegetation and logging road network in BTEC3 (ca. May 2003); (c) backhoe used during logging of BTEC3 in 2003–2004; (d) logged landscape of BTEC3 (ca. Feb 2004); (e) Amoozemeter on the cleared surface in ZOB3-POST.

selectively removed during the 1960s logging campaign. Much of the hillslope is now covered with mature, primary tree species (Fig. 2a). If roads or skid trails were constructed during the original logging, they are no longer discernable. A few walking paths do currently exist.

- *ZOB3* — A 0.14-ha zero-order basin in BTEC3 that was more disturbed than ZOB1, both in terms of the type of impact sustained during logging and logging frequency (Fig. 2b). ZOB3 was logged during the early 1960s, and then during a second logging campaign in 1999 high-value trees were removed. In general, hillslope disturbance during the latter logging was at most moderate (cf. Sidle et al., 2004); and it was mainly concentrated in areas where logs were yarded by tractors to landings (i.e., along skid trails). Crawler tractors transported cut logs from hillslopes to landings via a dense network of skid trails (about 170 m ha^{-1} for BTEC3 as a whole; Sidle et al., 2004).
- *ZOB3-POST* — ZOB3 following a recent, high-impact logging phase conducted from Dec 2003–Jan 2004, during which the remaining forest was clear-cut. The primary felling method in the upper catchment was felling the trees with a backhoe arm and scoop (Fig. 2c). The largest trees (>0.5-m in diameter) were felled by hand. Felled trees and understory vegetation were dragged with the backhoe arm across the hillslope and stacked into piles where they were burned. This method of removal required the creation of additional skid trails—referred to as 'terraces' because of their ostensibly low impacts and because they served as locations for replanted trees. No trees were removed for timber, as this operation was in preparation for plantation establishment.

In all we investigated three levels of disturbance to hillslope soils on the general harvest area: low (ZOB1, HILLSLOPE); moderate (ZOB3); and high (ZOB3-POST).

3. Measurements

3.1. K_s measurements

Saturated hydraulic conductivity was measured at five depths within the soil column (0.10, 0.25, 0.5, 0.75, 1.0 m) using the field-based, constant-head permeameter (aka the Amoozemeter; Amoozegar, 1992; Fig. 2e). The procedure involved augering a cylindrical hole of radius r to the desired depth, then establishing a constant head (H) such that $H/r \geq 5$ (Amoozegar and Warrick, 1986). During augering we attempted to minimize smearing and sealing of pores in the column walls by brushing the perimeter of the hole. Measurements were conducted until a steady-state flow rate (Q) was observed. We calculate K_s using the Glover solution (Amoozegar, 1989, 1992):

$$K_s = QA \quad (1)$$

where A is dependent on the depth (D_{IL}) to an underlying impermeable layer:

$$A = \begin{cases} \dfrac{\sinh^{-1}(H/r) - \left((r/H)^2+1\right)^{0.5} + r/H}{2\pi H^2} & \text{for} \quad D_{IL} \geq 2H \\ \dfrac{3\ln(H/r)}{\pi H(3H+2s)} & \text{for} \quad D_{IL} < 2H \end{cases} \quad (2)$$

For auger hole depths 0.25 m and below, r and H were 2.65 and 13.5 cm, respectively; these dimensions were 1.30 and 8 cm, for the 0.10-m depth.

We measured K_s at 10–12 locations in each of ZOB1, ZOB3, and HILLSLOPE during separate field campaigns in May 2003, June 2003, and February 2004, respectively (Fig. 1b). The ZOB1 measurements sites were concentrated in the lower half of the basin to avoid interfering with an ongoing experiment above (Fig. 1c). The ZOB1 and ZOB3 measurement locations were selected to cover the range of slopes in each basin (i.e., stratified sampling rather than random). At the HILLSLOPE location, K_s was measured at 15–20 m intervals along a transect extending from the hillcrest down to a location approximately 20-m above the stream channel (Fig. 1). None of these initial K_s measurements were performed on skid trails because we were focusing on identifying disturbance impacts on the non-roaded portion of the harvesting area. Understory vegetation and surface litter obscured surface conditions at all sites, therefore, our selection of measurement locations was not biased by a preconception of the level of disturbance.

We used the depth to saprolite/bedrock (determination method presented in Section 3.2) as the initial value of D_{IL} in Eq. (2). Following preliminary calculations of K_s within the profile at each measurement site, we modified D_{IL} for the following case:

$$K_1/K_2 \geq 10 \quad (3)$$

where K_1 is the K_s at any one of the "upper" measurement depths (i.e., 0.10–0.75 m), and K_2 is the K_s at one of the measurement depths below (McKenzie et al., 2002). If this situation occurred, D_{IL} was the distance between the two measurement depths. In some cases, we used a value of 0.

In February 2004, we conducted additional K_s measurements in ZOB3 (i.e., the ZOB3-POST treatment). During this campaign, we attempted to measure K_s in the immediate vicinity of the previous ZOB3 measurements (based on $x-y$ grid location). All of these locations had been disturbed by the logging operations; and at three sites, new terraces had been constructed. We conducted these measurements only at the 0.1- and 0.25-m depths. We also measured K_s at three locations on skid trails and at two additional terrace locations to characterize these additional logging disturbances.

3.2. Soil depth and horizon descriptions

At each K_s measurement location in ZOB1, ZOB3, and HILLSLOPE, we extracted a 1.25-m soil column with a

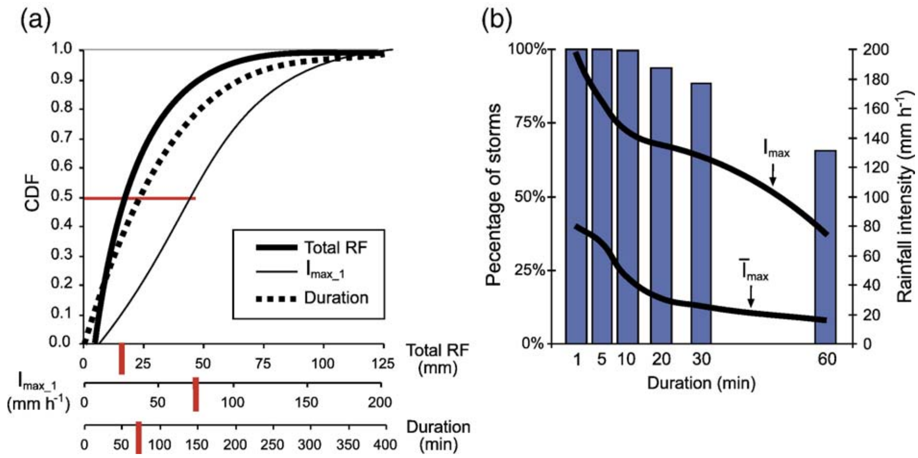

Fig. 3. Panel (a) shows for 264 storms the cumulative probability density functions (CDF) for total rainfall depth, maximum one-minute rainfall intensity, and event duration. The thick vertical lines in each of the *x*-axes correspond with a CDF value of 0.5. Panel (b) shows the percentage of 264 storms that had a 1, 5, 10, 20, 30, and 60-min sustained period of rainfall (bars; primary *y*-axis). Also shown in (b) are the maximum sustained rainfall intensities (I_{max}, calculated for all rainfall events) and the median maximum sustained ($\bar{I}_{max}$) rainfall intensities, calculated for $n \leq 264$ storms, depending on the length of each storms (secondary *y*-axis).

bore auger to demarcate site-specific soil horizon boundaries and to determine depth to bedrock in the case of shallow soils. Additionally, we estimated soil depth with a portable dynamic cone penetrometer (S06-M knocking pole penetrometer, Tsukubamaruto, Japan). The penetrometer provides an index of penetration resistance for regularly spaced intervals in the soil column. Specifically, penetration resistance is expressed as the number of knocking values (N_{c_10}), or drops of a 5-kg weight, needed to drive a 25-mm diameter cone 10 cm into the soil profile (Wakatsuki et al., 2003). Using the N_{c_10} values, the depths of important horizons were delineated as follows: (1) the mineral soil epipedon ($N_{c\_10} < 5$); (2) weathered subsurface layer ($5 \leq N_{c\_10} < 50$); and (3) saprolite or bedrock ($N_{c\_10} \geq 50$). We used the latter depth as the initial value of D_{IL} in the calculation of Eq. (2). If unavailable, information from the augered soil columns was used to determine D_{IL}.

At road cuts immediately adjacent to both ZOB1 and ZOB3, we examined 2-m soil profiles to obtain horizon-specific information on soil structure and selected physical properties, including the following: color (wet/dry); texture; bulk density (100-cm^3 cores); penetration resistance (pocket penetrometer); and vane shear strength (pocket torvane). Profiles determined at hand-dug pits at the HILLSLOPE site were described in a prior study (Noguchi et al., 1997b).

As a general indicator of near-surface disturbance at each K_s measurement site, we measured normal penetration resistance (NPR) with a portable cone penetrometer (DIK-5521; Daiki, Japan). The device records penetration resistance at 5-cm increments (down to a 60-cm depth) while being hand-pushed into the soil using constant pressure. At each site, duplicate measurements were taken at 5 locations (the approximate K_s site and 2-m away in each of the four cardinal directions).

Table 1
Soil physical properties for soil pit in ZOB1

Horizon[a]	A	B_{t1}	B_{t2}	B_{t3}	B_{t4}	B_{w5}	C_r
Extent (cm)	0–3	3–11	11–29	28–49	49–78	78–103	103–130+
ρ_d (g cm^{-3})[b]	0.73	0.78	0.89	1.10	1.29	1.52	1.67
PR (kg cm^{-2})[b]	<0.5	<0.5	0.50	1.25	2.00	2.25	2.75
τ_v (kg cm^{-2})[b]	0.03	0.04	0.10	0.23	0.28	0.30	0.40
w (g (H_20)/g (soil))[c]	0.26	0.28	0.29	0.36	0.25	0.29	0.30
Color	10YR3/4	10YR5/6	7.5YR6/6	7.5YR7/6	7.5YR6/6	7.5YR7/6	10YR8/4
Sand (%)	32	36	35	31	37	44	–
Silt (%)	32	23	23	24	24	27	–
Clay (%)	36	41	42	45	40	29	–
Rock content (%)	<1	<1	<1	30–40%	50	>50	Saprolite
Nature of rock[d]	na	na	na	Gravel	Pebble	Fragments	Massive
Root abundance	Many	Many	Some	Few	None	None	None

[a] Subscripts for B_t and B_w refer to clay-rich and weathered B horizons, respectively; C_r is saprolite.
[b] ρ_d is bulk density determined for a 100 cm^3 core; PR is penetration resistance determined with a pocket penetrometer; τ_v is vane shear strength.
[c] w is the wetness at which all other properties were determined.
[d] All rock material was highly weathered; gravel and pebbles were predominately quartz; fragments resembled the underlying bedrock.

Table 2
Soil physical properties for soil pit in ZOB3

Horizon[a]	A	B_{t1}	B_{t2}	B_{t3}	B_{t4}	B_{w5}	C_r
Extent (cm)	0–3	3–32	32–57	57–71	71–90	90–110	110–130+
ρ_d (g cm^{-3})[b]	0.77	0.87	1.20	1.38	1.59	1.63	–
PR (kg cm^{-2})[b]	<0.5	<0.5	0.50	1.30	2.25	>3.0	>3.0
τ_v (kg cm^{-2})[b]	0.03	0.05	0.10	0.20	0.30	–	–
Color (dry)	10YR5/3	10YR7/4	10YR8/6	10YR7/6	7.5YR7/6	7.5YR6/8	10YR8/4
Sand (%)	40	39	40	41	47	60	56
Silt (%)	22	19	10	15	17	22	19
Clay (%)	38	43	49	44	36	18	24
Rock content (%)	<1	<1	<1	30–50	40–60	>50	Saprolite
Nature of rock[c]	–	–	–	g and sp	p>sp>g	–	–
Root abundance	Many	Some	Some	Few	None	None	None

[a] Subscripts for B_t and B_w refer to clay-rich and weathered B horizons, respectively; C_r is saprolite.
[b] ρ_d is bulk density determined for a 100 cm^3 core; PR is penetration resistance determined with a pocket penetrometer; τ_v is vane shear strength; all variables were determined for wetness values of 0.25–0.30 g (H_20)/g (soil).
[c] All rock material was highly weathered; gravels (g), small pebbles (sp), and pebbles (p) were predominately quartz.

3.3. Piezometer measurements

In ZOB1 we established three piezometer nests, each consisting of two piezometers (Fig. 1; Negishi et al., in press). One piezometer was installed to the depth below the saprolite layer (i.e., >1.0 m); the other at a depth corresponding with the B_t–B_w horizon boundary at that location (e.g., 0.47, 0.54, and 0.42 m, for PZ1, PZ2, and PZ3, respectively). Piezometers were constructed from 5-cm diameter PVC pipe; the bottom 0.2-m of each was perforated and covered with 233-μm Nitex net to prevent sedimentation. Piezometric responses at 3-min intervals were monitored continuously using water level sensors (WHR, TruTrack, NZ) from April to November 2004 to investigate the occurrence of subsurface water rising to the soil surface. Specifically, we were looking for the simultaneous occurrence of positive head in the shallow piezometer and head in the deep piezometer that was lower than the depth of the bottom of the shallow piezometer. This situation would support the development of a perched water table.

3.4. Rainfall measurements

Rainfall was measured from Nov 2002 to Dec 2004 with an Onset (Pocasset, MA) 20.3-cm diameter tipping bucket rain gauge and Hobo logger. The initial location of the rain gauge was an open area in BTEC3, but was moved in Dec 2003 to a nearby location to avoid logging operations (Fig. 1b). Storms were defined as events totaling at least 5 mm, without having a rain-free gap >1 h (Negishi et al., 2006).

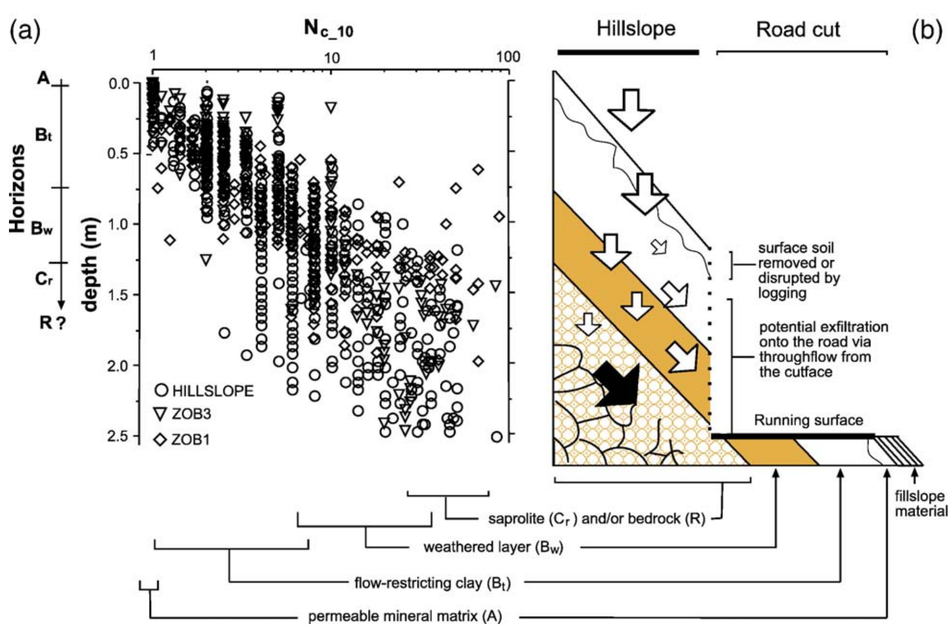

Fig. 4. (a) Comparison of N_{c_10} values (via knocking pin penetrometer, see text) with soil depth in the three measurement locations. (b) Idealized flowpath movement with respect to K_s within the soil profile (white arrows); storm throughflow moving along these flowpaths is commonly intercepted by the road cuts. The black arrow indicates groundwater, which is likely a combination of pre-event and event water.

Table 3
Depth to weathered layer and bedrock; and normal penetration resistance

Variable	Units	HILLSLOPES	ZOB1	ZOB3	ZOB3-POST
D_w	m	0.9±0.1	0.8±0.1	0.7±0.0	–
D_R	m	2.0±0.4	1.4±0.2	1.2±0.2	–
NPR (0 m)	kg cm^{-2}	1.8±0.4	3.4±0.3	4.5±1.0	1.8±0.3
NPR (0.3 m)	kg cm^{-2}	10.0±3.4	7.9±1.1	8.9±1.5	8.3±1.7
n		11	10	9	5

D_R and D_{IL} are depths to the weathered layer and saprolite/bedrock, respectively (determined with the knocking pin penetrometer); NPR is normal penetration resistance at depths 0 and 0.3 m (determined with the DIK-5521 cone penetrometer). Values are medians±one median absolute deviation; n is sample number.

3.5. Site disturbance index

In February 2004, following the mechanized clear-cut operations (i.e., ZOB3-POST), we performed a post-logging survey of surface disturbance in ZOB3 (modified from Murphy (1982) and Rab (1996)). Within a 5-m radius at each K_s measurement site, we estimated visually the percentage of area that corresponded to the following mutually exclusive disturbance categories: (1) new terraces were created; (2) exposed and compacted subsoil soil; (3) exposed subsoil; (4) exposed topsoil; (5) disturbed litter layer; and (6) no obvious surface disturbance. The values were averaged to estimate the total level of disturbance for the ZOB3-POST treatment. Additionally, percentage of area burned was estimated in the same locations.

4. Results

4.1. Rainfall

We recorded 264 storms during the 25-month measurement period (Negishi, 2006). Median values for total rainfall and storm duration were 16 mm and 83 min, respectively. Half of the recorded one-min rainfall intensity values were $\geq$80 mm h^{-1} (Fig. 3a). The absolute maximum 1-, 5-, 10-, 20-, 30-, and 60-min intensities ($I_{1_max}, \ldots, I_{60_max}$) for all storms were 200, 164, 146, 136, 130, and 74 mm h^{-1}, respectively (Fig. 3b). The median maximum sustained 1-, 5-, 10-, 20-, 30-, and 60-min intensities ($\bar{I}_{1_max}, \ldots, \bar{I}_{60_max}$) were 80, 56, 45, 32, 25, 17 mm h^{-1} (Fig. 3b). Below, we use these absolute and median maximum intensity values as indices for identifying hydrologically-significant site-related differences in K_s.

4.2. Soil properties

Physical and structural properties determined for the road-cut profiles near ZOB1 and ZOB3 are shown in Tables 1 and 2. Here we assume these disturbed road-cut profiles are representative of the soil profiles on the non-roaded hillslopes of ZOB1 and ZOB3. Thus, the soils in both basins were characterized by shallow A horizons with thick root masses, underlain by 0.7–0.9 m of clay-rich material. Clay contents in these B_t horizons range from 35% to 50%. Within the first 0.6 m, bulk density (ρ_b) increased by about 50%; penetration resistance (PR) and vane shear strength (τ_v) increased an order of magnitude. Rock content increased to approximately 50% in the B_w horizon (starting at about 0.8–0.9 m); this depth range corresponded roughly with a median N_{c_10} value of 5 (Fig. 4a). The B_w horizon gave way to saprolite and/or bedrock at a depth of approximately 1.1–1.3 m. Similarly, the N_{c_10} data from both sub-catchments indicated the median depth to saprolite/bedrock was 1.2–1.4 m (Table 3).

Table 4
Descriptive statistics for K_s (mm h^{-1}) at depth for three sites/treatments

	0.1 m	0.25 m	0.5 m	0.75 m	1.0 m
HILLSLOPE					
Median	1493	229	13	3	2
MAD	784	209	10	2	1
Mean	1443	393	148	8	3
Standard deviation	988	400	240	15	2
CV	0.69	1.02	1.62	1.99	0.82
IQR	1734	694	277	4	3
Minimum	122	21	2	<1	<1
Maximum	3122	1090	735	54	7
Geometric mean	1013	183	25	3	2
Harmonic mean	572	72	7	1	1
Skewness	0.1	0.6	1.5	2.7	2.1
n	11	11	12	11	11
ZOB1					
Median	676	160	20	2	1
MAD	416	75	17	2	1
Mean	994	166	111	7	2
Standard deviation	694	126	159	14	3
CV	0.70	0.76	1.43	2.08	1.39
IQR	1280	156	206	5	2
Minimum	203	7	2	0.1	0.1
Maximum	2148	434	492	46	8
Geometric mean	772	108	31	2	1
Harmonic mean	584	46	9	<1	<1
Skewness	0.5	0.8	1.5	2.6	1.5
n	10	10	10	10	10
ZOB3					
Median	189	33	16	8	4
MAD	172	15	9	4	2
Mean	596	34	64	7	4
Standard deviation	744	48	89	8	4
CV	1.25	2.56	1.65	0.63	0.78
IQR	1050	51	147	5	3
Minimum	13	3	3	1	<1
Maximum	2003	174	365	17	9
Geometric mean	191	15	25	6	2
Harmonic mean	60	2	11	3	1
Skewness	1.0	1.8	1.4	0.1	0.3
n	12	9	10	9	8

MAD, CV, and IQR are median absolute deviation, coefficient of variation, and interquartile range. Variations in sample number (n) within tested treatments reflect omission of values that were subject to measurement errors (e.g., violation of the assumptions involving Eq. (2), Amoozegar and Warrick, 1986).

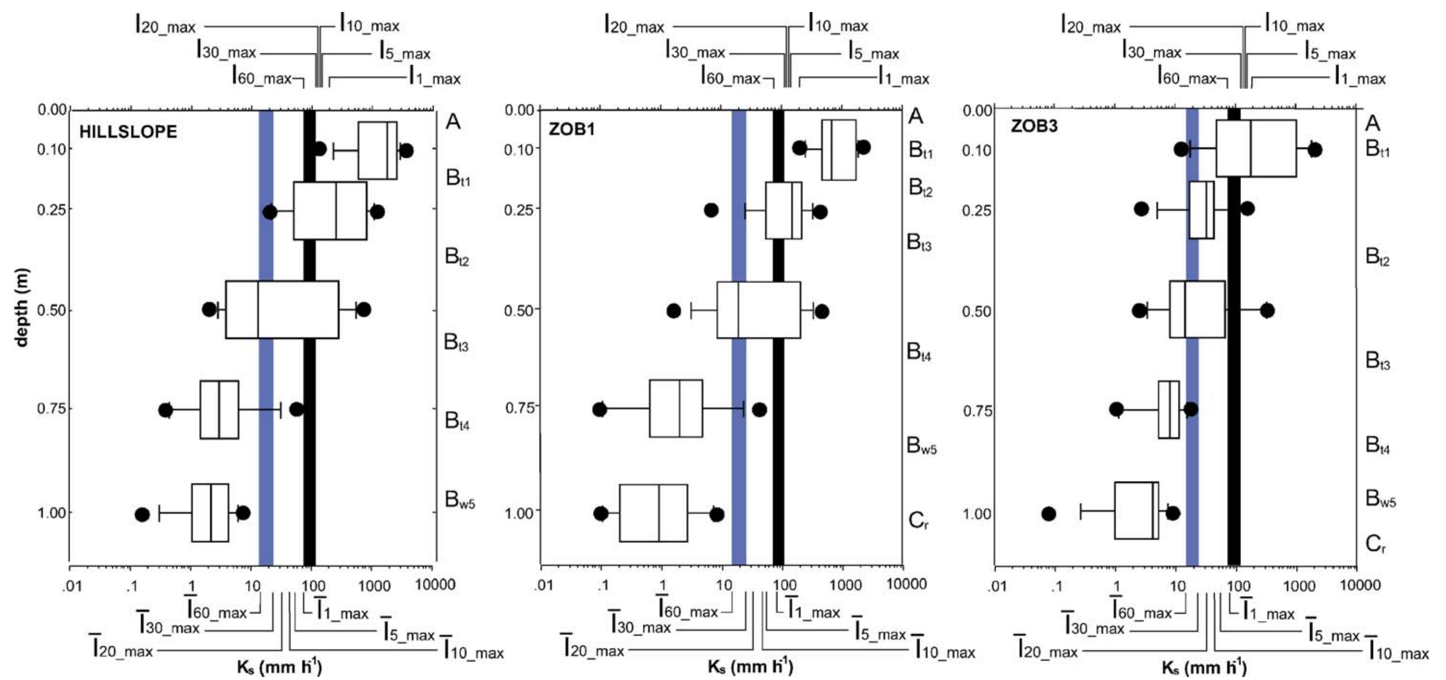

Fig. 5. Box plots of K_s at five depths for the three measurement locations (Fig. 1). Box plot features shown include the following: median, inter-quartile range (rectangle), 10th and 90th percentiles (whiskers), and outliers (circles). I_{n_max} values are the maximum n-min rainfall intensities (based on 264 observed storms); and $\bar{I}_{n\_max}$ values are the median sustained n-min rainfall intensities. The black bar shows the range of I_{60_max}–I_{30_max} values (74–130 mm h^{-1}); the gray bar highlights the range for the $\bar{I}_{60\_max}$–$\bar{I}_{30\_max}$ values (17–25 mm h^{-1}).

Table 5
K_s (mm h^{-1}) determined at two depths for ZOB3 and ZOB3-POST treatments

Surface	0.10 m	0.25 m	Sample size
Hillslope soils (ZOB3, before 2004 logging)	189 ± 172	38 ± 15	(12, 9)
Hillslope soils (ZOB3-POST)	107 ± 79	22 ± 17	(9, 9)
New terraces (within ZOB3-POST)	455 ± 365	2 ± 0	(5, 5)
Skid trails (within ZOB3-POST)	5 ± 3	2 ± 0	(3, 3)

K_s values are medians ± median absolute deviations.

Total soil depth on HILLSLOPE, also determined with the knocking pole penetrometer in the prior study (Noguchi et al., 1997a), was deeper (median ≈ 2.0 m; range of 1.2–5.7 m). Other horizon-specific data for HILLSLOPE were similar to those from ZOB1 and ZOB3 (e.g., bulk density, color, texture, rock content macro-porosity, organic matter; Noguchi et al., 1997a; unpublished data). Despite the discrepancy in depth, the general similarity in soil structure and physical properties suggested that the soils at all three sites belong to the same series — the *Kuala Brang* Orthoxic Tropudult.

4.3. Saturated hydraulic conductivity

Preliminary examination using the Shapiro–Wilk's *W*-test indicated that the distributions of most of the depth-related K_s data sets were close to lognormal, as reported by others (e.g., Rogowski, 1972; Warrick et al., 1977; Talsma and Hallam, 1980). However, owing to high variability, AVOVA and post hoc tests of log$_{10}$-transformed K_s data were only marginally useful in identifying statistically significant groupings that aided in explaining important hydrologically-significant patterns at any one site, or among the three sites. Non-parametric tests were equally ineffective. We therefore simply compared box plots describing the K_s data with absolute and median maximum rainfall intensity values to identify hydrologically important differences among the treatments.

Saturated hydraulic conductivity decreased with increasing depth from the surface at all three sites (Table 4). The 2–3 orders of magnitude decrease in K_s from 0.1 m to 0.75 m is shown in Fig. 5. Observed patterns and magnitude of K_s were similar at HILLSLOPE and ZOB1 sites in the following respects: all 0.1-m K_s values plotted above the $\bar{I}_{1\_max}$ value; (2) median K_s for the 0.25-m depth plotted above the I_{10_max} value; (3) median 0.5-m K_s was less than $\bar{I}_{30\_max}$ (although variability was much higher at HILLSLOPE); and (4) median K_s at 0.75 and 1.0 m plotted below the $\bar{I}_{60\_max}$ value. In contrast, the ZOB3 K_s data differed from HILLSLOPE and ZOB1 in that variability in the 0.1-m measurements was much greater, and median 0.25-m K_s was substantially lower. For all three sites, K_s at or below 0.5 m was indistinguishable. Based on these relationships, we conclude that the only major differences in K_s among the three sites/treatments were within the upper 0.25 m at ZOB3.

Following the 2004 logging phase, median K_s at 0.1 m dropped from 190 to about 110 mm h^{-1} (i.e., ZOB3 versus ZOB3-POST treatments, Table 5). The median value at 0.25 m also decreased slightly. Owing to high variability within these small data sets, we do not consider these differences to be significant (Fig. 6).

4.4. Piezometer response

A total of 75 storms were recorded during the 8-month period when the piezometers were operational in ZOB1. Only during the following two storms did we detect head values that would be in line with the development of a perched water table: (1) 29 April 2004 at PZ2 (storm depth, duration, and I_{max_30} = 81 mm, 120 min, and 104 mm h^{-1}); and (2) 4 July 2004 at PZ1 (depth, duration, and I_{max_30} = 76 mm, 89 min, and 83 mm h^{-1}) (Table 6). A total of 16 storms occurred in the month prior to the 29 April event; the 30-day antecedent precipitation index (API$_{30}$) was 219 mm. In contrast, the 4 July storm occurred

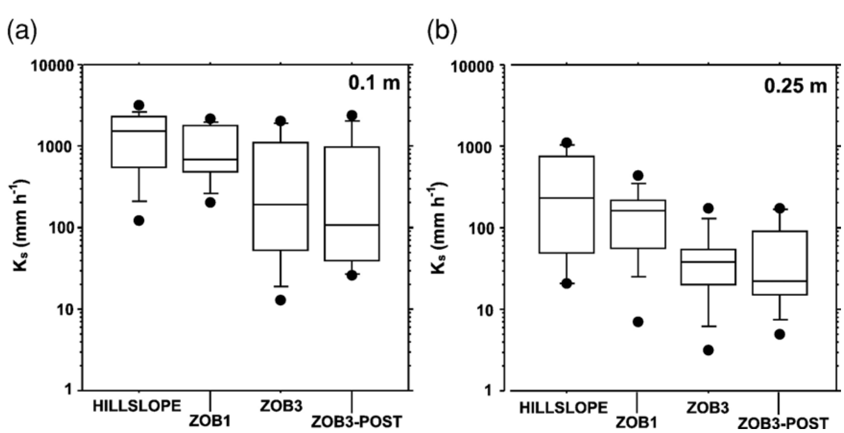

Fig. 6. Box plots of K_s at 0.10- and 0.25-m depths for the HILLSLOPE, ZOB1, ZOB3, and ZOB3-POST treatments. Box plot features shown include the following: median, inter-quartile range (rectangle), 10th and 90th percentiles (whiskers), and outliers (circles). Sample numbers and descriptive statistics for the four treatments are listed in Table 5.

Table 6
Rainfall and antecedent moisture conditions for the seven largest recorded storms (sorted by I_{max_60}) during the period Nov 2002–Dec 2004

Date	D_{RF} (mm)	d_{RF} (min)	I_{1_max} (mm h^{-1})	I_{10_max} (mm h^{-1})	I_{30_max} (mm h^{-1})	I_{60_max} (mm h^{-1})	API_{10} (mm)	API_{30} (mm)	d_{PWT} (min)	D_{med} (mm)	D_{max} (mm)
29-Apr	80.9	120	200	142	104	74	27	219	18 (PZ2)	13	28
2-May	126.8	389	180	144	109	71	61	289	na	na	na
4-Jul	76.2	89	120	104	83	67	0	0	24 (PZ1)	36	77
13-Nov	82.5	232	140	122	101	67	203	447	–	–	–
6-May	64.2	68	160	104	78	63	252	448	–	–	–
9-Nov	78.9	299	160	134	103	59	254	398	–	–	–
5-Nov	79.2	127	160	102	77	56	138	283	na	na	na

D_{RF} is rainfall depth; d_{RF} is rainfall duration; I_{n_max} values are maximum 1-, 10-, 30-, and 60-min rainfall intensities; API_n is the antecedent precipitation index for the prior 10 or 30 days (i.e., total depth of rainfall in the respective period); d_{PWT} is the duration that a perched water table formed at either piezometer location 1 or 2 (Fig. 1c); D_{med} and D_{max} are the median and maximum piezometer head during occurrence of the perched water table; 'na' indicates that the piezometers were not installed during this storm; the '–' indicates that a perched water table did not form during the storm.

following a prolonged dry period, for which the API_{30} was 0 mm.

Periods during the two storms when head in the deep piezometer was less than that in the corresponding shallow piezometer were however short-lived. Owing to subsurface convergent flow or seepage (exfiltration) from the bedrock, head in the paired piezometers became equal in a matter of minutes (24- and 18-min at PZ1 and PZ2, respectively, Table 6). Maximum head in the shallow piezometers was 77 and 28 mm, respectively. Thus, the height of the perched water tables, if indeed they formed, would have been less than or equal to these values, and still 0.4–0.5 m below the soil surface. In these two cases, it is possible that the head differences may be related to microtopographic dissimilarities between the two piezometer pairs, rather than a perched water table development. In the discussion below however, we assume that a perched water table did form during the two storms.

In a prior study conducted at the HILLSLOPE location (Noguchi et al., 1997a), a perched water table was observed in response to a 44-mm rainfall event (max intensity= 36 mm h^{-1}). The evidence supporting this occurrence, however, was only a singular reading of a mercury manometer tensiometer.

5. Discussion

5.1. Depth-specific patterns in K_s

The decrease of K_s with depth at the HILLSLOPE and ZOB1 sites is probably representative of the natural case for forested hillslope soils in BTEC. High K_s values at the 0.10-m depth are maintained by a thick layer of roots and other biotic activity that occur near the surface. Maximum measured K_s values were >2000 mm h^{-1}. We attribute the decline in K_s of two orders of magnitude over a depth increment of 0.5 m to the clay-rich subsurface soil (B_t horizon), which has a substantially higher bulk density, normal shear strength, and vane shear strength than the epipedon (inferred from Tables 1 and 2). In the depth interval 0.5 to 1.0 m, some of the clay content is replaced by sand; and weathered rock fragments (*b*-axis median ≈ 1 cm) comprise about 50% of the soil matrix (Tables 1 and 2). Compared with the B_t horizon at about 0.50-m, ρ_b, PR, and τ_v were about 20%, 80%, and 30% higher in the lower weathered horizons. It was at depths ≥0.75 m that K_s typically dropped to below 10 mm h^{-1} (minimum values were less than 0.1 mm h^{-1}, Table 4).

5.2. Uncertainty in K_s

The 3-orders-of-magnitude decrease in median K_s within the upper 1 m of soil contradicts findings of a prior study conducted at the HILLSLOPE site. Using a constant-head permeameter method on extracted, vertically-oriented soil cores, the prior study found median K_s values down to 0.8 m were greater than about 200 mm h^{-1} (Noguchi et al., 1997b). Dissimilarity in K_s between the two studies likely results from differences in the measurement method. Talsma and Hallam (1980), for example, questioned if their observed differences in hydraulic conductivity were related to the method employed (core versus well-permeameter). They further state that measurement-related differences could be up to an order of magnitude (cf. Topp and Binns, 1976; Sherlock et al., 2000). Specifically, pore closure and/ or disruption of pore continuity by augering and infiltrating water are reasons commonly given for underestimation of hydraulic conductivity using well permeameters—when compared with core-based values (Talsma, 1987; cf. Koppi and Geering, 1986; Wilson et al., 1989; McKay et al., 1993; Campell and Fritton, 1994; Sherlock et al., 1995; Davis et al., 1999).

We concede that the method used in our study is likely prone to underestimating K_s in the clay-rich horizons, owing to smearing and blocking of pore entry when preparing the hole, despite our precautionary measures. However, results from a prior staining experiment in BTEC support our observed depth-related K_s patterns (Noguchi et al., 1997b). Excavation of rainfall simulation plots following sprinkling of a white dye solution at a rate of 80 mm h^{-1} for 30 min showed that infiltrating water was deflected laterally below the A horizon. This zone of deflection corresponds with the clay-rich B_t sub-horizons. At a depth of 0.2–0.3 m, dye was only detectable in 3–14% of the plot areas. Because of the similarity between the staining pattern in the prior study and our K_s data, we believe our new measurements are realistic indicators of relative values of subsurface K_s—despite our uncertainty in the absolute values (cf. Talsma, 1987; Sherlock et al., 2000).

5.3. Perched water table formation

Several studies have reported depth-related decreases in near-surface K_s in tropical soilscapes (e.g., Bonell and Gilmour, 1978; Elsenbeer et al., 1992; Malmer, 1996; Elsenbeer et al., 1999; Sherlock et al., 2000; Godsey and Elsenbeer, 2002; Sobieraj et al., 2002; Ziegler et al., 2004); one notable exception is reported by Dykes and Thornes (2000). The hydrogeomorphic significance of such a decline is that a perched water table can form where K_s is exceeded by sustained rainfall intensity (Elsenbeer, 2001). If this lower K_s layer occurs at a shallow depth, saturation overland flow may occur during high-intensity rainfall (Bonell and Gilmour, 1978; Elsenbeer and Lack, 1996). Alternatively, high slope-parallel fluxes of subsurface water (e.g., for the case of high K_s above the impeding layer and steep slopes) could contribute to return flow downslope. Specifically for Bukit Tarek, the depth at which the natural reduction in K_s could possibly cause a perched water table is about 0.5 m (Fig. 6), which is the depth at which infiltrating water was deflected laterally in the prior staining experiment (Noguchi et al., 1997b). Furthermore, median maximum sustained 30-min rainfall intensity exceeds the median 0.5-m K_s values at all three sites (Fig. 5). Note that in the comparisons of K_s and rainfall intensity in Fig. 5, we do not account for alterations in rainfall intensity related to interception by vegetation.

We detected a perched water table only twice during the 8-month period when the piezometers were operational (Negishi et al., in press). This period included five of the seven largest recorded storms (Table 6). For the two events when a perched water table did form, it was quickly inundated by groundwater rising from below. During the prior staining study, infiltrating water was observed flowing preferentially along masses of both living and decayed roots, providing evidence that event water moved quickly into the subsurface soil (cf. Weiler and Naef, 2003; Weiler and Flühler, 2004). This capability to bypass some portion of the low-K_s subsoil may contribute to the observed rapid rise of the local water table. In neither of the two events did surface saturation occur in the vicinity of the piezometer nests, suggesting that even if a prolonged perched water table were to form at about 0.5 m, this depth is too great to saturate soils during storms of the magnitude we recorded, except at points of converging subsurface flow (Negishi et al., in press). Therefore, the situation observed by Bonell and Gilmour (1978), where a perched water table forming at a depth of 0.2-m generated saturated overland flow during high-intensity storms, does not appear to be a common runoff generation mechanism in BTEC.

5.4. Impacts of logging on hillslope Ks

Comparison of Ks in the four logging treatments supports the following interpretations regarding disturbance and recovery of hillslope soils (Figs. 5 and 6):

1. Disturbance at the low-impact, selective logging sites (HILLSLOPE and ZOB1) is probably no longer important in terms of infiltrability, either because the initial disturbance was minimal and/or the soil K_s has recovered substantially in 40 years since logging;
2. The comparatively higher-impact, mechanized logging that took place in ZOB3 in 1999 probably caused substantial disturbance within the upper 0.25-m of the soil profile. This manifests as high variability in near-surface K_s (0.10 m)—and possibly, the substantially reduced K_s at the 0.25 m depth. Thus, only limited recovery in infiltrability had occurred during the subsequent 3 year period; and this may be related to vegetation growth and other biological activity primarily within the upper 0.1 m.
3. The most recent mechanized, clear-cutting campaign visually disturbed the soil surface, but no substantial changes in K_s in the upper 0.25-m soil profile could be distinguished on non-road/track areas.
4. None of the timber extraction methods reduced K_s at 0.5 m or below in the hillslope soils. This no-impact depth may even be shallower, for we are uncertain about the true cause of the lower K_s at 0.25 m in ZOB3.

Again we draw these interpretations without having a true undisturbed forest control treatment. In addition, although the measurements at each site were replicated 9–12 times, the treatments themselves are not replicated—a flaw that prevented us from using statistical tests such as ANOVA to verify treatment-related differences (cf. Hurlbert, 1984). Without such replication we cannot unequivocally state that the comparative low K_s at the 0.25-m depth in ZOB3 is related to differences in logging activity, and not some other phenomenon (i.e., item 4 above).

Other researchers recognize that disturbances to the hillslope portion of the harvest area are often highly variable in both spatial extent and severity, but in comparison with roads and skid trials, disturbances are much less intense (cf. Sidle and Shaw, 1983; Sidle and Laurent, 1986; Huang et al., 1996; Rab, 1996; Brooks and Spencer, 1997; Croke et al., 1999; Rab, 2004). This is also true in BTEC3. During the 2003–2004 logging operations, hillslope disturbance was severe, especially in the upper catchment where ZOB3 was located. Our February 2004 post-logging survey revealed the following information about disturbance area in ZOB3: new trails/terraces created (5%); subsoil exposed and compacted (20%); subsoil exposed only (40%); topsoil exposed only (25%); litter layer disturbed only (5%); and no surface disturbance (<5%). Such levels of ground disturbance are very high, even for ground-based logging. The large extent of the disturbance during 2003–2004 in BTEC3 was related, in part, to the construction of numerous small terraces (implemented by cutting small skid trails into the hillslope) for the purpose of plantation establishment. Approximately 80% of the surface area in ZOB3 was burned, with relatively deep burning occurring on about 20% of the hillslopes. Despite the high level of surface disturbance (Fig. 2b and d), K_s was not greatly reduced (Fig. 6). Nevertheless, overland flow was generated more frequently on these disturbed hillslopes following logging (based before and after observations), possibly because Hortonian overland flow was generated in some areas following rainfall-induced surface sealing on unprotected soils (Morgan, 1995). Burning have also have facilitated this process by promoting water repellancy (Wilson, 1999; Robichaud, 2000).

The degree to which soil compaction on the harvest area contributes to long-lasting changes in K_s that would trigger Hortonian overland flow generation or alter subsurface flow pathways is not straightforward. In prior works showing compaction-related changes to hydrological variables following logging (often extending down to about 0.25 m), disturbance was typically related to the passing of heavy logging machinery (e.g., Van der Plas and Bruijnzeel, 1993; Aust et al., 1995; Huang et al., 1996; Rab, 1996). During the most recent logging operations in BTEC, crawlers and backhoes did not extensively traverse the harvested hillslope except for on roads and skid trials (i.e., used for yarding and terrace construction); this is probably also true for the early logging operations that affected ZOB1 and HILLSLOPE. Very limited compaction may have occurred related to impact of felled trees; more substantial and widespread compaction may have occurred from yarding stand stacking trees prior to burning and ground contact with the backhoe bucket. However, such impacts typically cause much less and shallower compaction compared with that attributed to multiple passes of heavy machinery (Dickerson, 1976; Sidle and Drlica, 1981). The observed minor changes in near-surface K_s in the harvest area following the 2003–2004 logging activity was therefore most likely attributable to topsoil removal and mixing with the subsoil by the activities mentioned above.

5.5. Terraces and skid trails

Here, we touch briefly on road-related impacts because some of the original hillslope K_s measurement sites in ZOB3 were converted to terraces during logging. Various types of road-related impacts are addressed in detail elsewhere (Sidle et al., 2004; Negishi et al., 2006). In locations in ZOB3-POST where terraces had been built on the original measurement spot, median K_s at 0.25-m decreased to 2 mm h^{-1} (Table 5). In contrast, the median 0.1-m K_s value on terraces increased significantly. Median K_s on skid trails was ≤ 5 mm h^{-1} at both the 0.1-m and 0.25-m depths. Comparatively low K_s/infiltration values associated with skid trails are well known (e.g., Malmer and Grip, 1990; Bruijnzeel and Critchley, 1994; Brooks and Spencer, 1997; Croke et al., 1999; Startsev and McNabb, 2000). At first inspection, the newly created terraces appeared to reduce this type of impact on infiltrability. In particular, the median 0.1-m K_s value for terraced surfaces was about 460 mm h^{-1}, which is roughly 4 times higher than that found on the hillslope (Table 5). We attribute high K_s to the presence of side-cast material on the terrace surface where we took the measurement.

By the time of a follow-up inspection in November 2004, much of the unprotected, loose surface side-cast material on the terraces had been eroded during several high-intensity rainfall events. The presence of high K_s was therefore short-lived at these specific terrace sites. After removal of this loose surface layer, the terrace K_s values were therefore probably similar to those of the skid trail (≤ 5 mm h^{-1} for 0.1 and 0.25 m depths; Table 5), because both surfaces were cut into the soil profile more than 0.5 m. These K_s values are low enough to facilitate the generation of Hortonian overland flow during most seasonal events. For example, maximum 10-min rainfall intensity for more than 95% of the 264 storms exceeded the median skid trail K_s value.

5.6. Logging effects on stormflow generation

The high variability in shallow K_s following the recent logging disturbance in ZOB3 is somewhat typical of ground-based logging operations (e.g., Brooks and Spencer, 1997; Croke et al., 2001). Inferring effects on hydrological pathways from mean/median K_s derived from small-scale measurements is problematic. While isolated, compacted patches of the hillslope may experience Hortonian overland flow, downslope area of higher K_s can possibly infiltrate it. An important consideration is therefore the continuity and connectiveness of these overland flow source areas. Important in ZOB3 after logging was the interaction of compacted areas with skid trails and roads, which provide linked corridors that transported overland flow and sediment long distances—often directly to the stream (Sidle et al., 2004).

Furthermore, the observed depth-related decline in K_s may be most important on the highly degraded hillslopes where the following have occurred: (1) some portion of the upper topsoil has been removed, effectively reducing the depth at which a perched water table would form; (2) deep rooted vegetation has been replaced with shallow-rooted plants, thereby diminishing the ability of event water to quickly reach the groundwater table; and (3) a high density of road cuts creates many opportunities for interception of subsurface flow (Fig. 4b). Importantly, the shallow, horizontally-aligned root systems of the *Kelet-kendondong* vegetation association facilitates the development of near-surface pipes that terminate at the road cutface (Noguchi et al., 1997a). It is through such pipes that event water often flows from the subsoil onto the road surface. Thus, interaction between the decline in subsurface K_s, presence of biogenic pipes, and a high-density of logging roads, augment the generation of overland on the road surface. The consequence of these additional sources of surface runoff is great because BTEC3 roads are important discharge agents for sediments and nutrients entering the stream (Sidle et al., 2004; Negishi et al., 2006).

5.7. Recovery time

Negative impacts on soil hydrologic properties associated with mechanical disturbance have been demonstrated to linger anywhere from a few years up to half a century (cf., Dickerson, 1976; Froehlich, 1979; Greacen and Sands, 1980; Jakobsen, 1983; Incerti et al., 1987; Malmer and Grip, 1990; Kamaruzaman, 1996; Croke et al., 2001; Rab, 2004). Recovery time depends in part on the variable in question and on the degree of disturbance. It is also affected by climate (e.g., weathering, freeze–thaw), variables related to revegetation (e.g., root activity), soil type, and additional anthropogenic activity. Nonetheless, it is well-established that compaction inhibits vegetation regeneration (Froehlich, 1979; Kozlowski, 1999). Vegetation recovery on exposed, nutrient-poor sub-horizons can be particularly slow, as recently demonstrated for two pioneer tree species in Sabah Malaysia (Nussbaum et al., 1995; but also see Woodward, 1996).

One of our initial goals was to estimate the recovery time for K_s following the disturbances in ZOB3. Hindering this estimate was our inability to quantify with certainty the extent of the impact to sub-surface flow pathways—in part because K_s may not be the best metric. At most we can comment about the observed increase in variability of K_s at the 0.1-m depth following the clear-cutting in 2003/2004 (Fig. 6). If we assume that the 1960s logging activities affected near-surface K_s similarly at ZOB1 and HILLSLOPE then we can estimate the time of recovery for the K_s on the non-roaded hillslope in ZOB3 to be no more than 40 years.

6. Summary

Abrupt decreases of two-to-three orders of magnitude in saturated hydraulic conductivity were measured within the upper 1.0-m soil profile at the BTEC site. This natural reduction in K_s that occurs by the 0.5 m depth is sufficient to produce the development of a perched water table, which in turn could facilitate the generation of saturation overland flow. Piezometer data indicated, however, that perched water table development was rare, was short-lived when it did form, and occurred too deep in the soil profile to cause saturation on planar hillslopes during typical events.

At sites where selective logging was conducted in the early 1960s, near-surface K_s on non-roaded hillslopes was higher than sustained rainfall intensities. This may reflect relatively low initial logging impact, but it is also probably indicative of the degree of recovery since disturbance. In contrast, a basin disturbed by mechanized logging in 1999, had a median K_s value at 0.25 m that was below the sustained 30-min rainfall intensity during 28% of 264 monitored storms. Re-measurement of K_s following a high-impact clear-cutting campaign in 2004 showed no discernable additional reductions to K_s. Variability in K_s at 0.1 m did however increase as a result of substantial subsoil exposure and topsoil–subsoil mixing. Inter-comparison of the three study locations suggest that logging-induced reductions in near-surface K_s on hillslopes recovers dramatically within 40 years.

Although we use saturated hydraulic conductivity as a metric to judge logging related disturbances to stormflow pathways, it may not be the best indicator of such phenomena, owing to issues related to the scale at which hillslope runoff processes propagate. Connectivity of overland flow source areas is also important. Changes to preferential flow phenomena also dictate the overall effect of disturbance on hillslope hydrologic response. Furthermore, these results should be viewed as preliminary because the logging treatments were not replicated and we lacked an undisturbed forest control.

Acknowledgements

Funding for this field research was provided by the National University Singapore grant #R-109-000-031-112 to R.C. Sidle, in collaboration with Forest Research Institute Malaysia (FRIM) and Japan International Research Center for Agricultural Sciences (JIRCAS). Junjiro Negishi was supported by a National University Singapore (NUS) Graduate Fellowship and Singapore Millenium Scholarship. Support for Alan Ziegler was provided by NUS and a Japan Society for the Promotion of Science (JSPS) fellowship. Roy Sidle was partly supported by a JSPS grant. We also thank Mamoud and Linda for their assistance.

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