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Soil Physical Properties and Preferential Flow Pathways in Tropical Rain Forest, Bukit Tarek, Peninsular Malaysia

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Soil physical properties and water movement within soil were investigated using dyes in a tropical rain forest, the Bukit Tarek Experimental Watershed of Peninsular Malaysia. The saturated hydraulic conductivity (K_s) decreased with increasing soil depth. The K_s values were higher than those reported for other tropical soils. The geometric means of the K_s values ranged from 4.69×10^{-3} (80 cm) to 4.07×10^{-2} cm s^{-1} (10 cm). This suggests saturation overland flow may not be dominant but that subsurface flow must play an important role in stormflow generation. The shapes of the soil moisture characteristic curves resembled those of forest soils which have large changes in volumetric water content at pressure heads < 30 cmH_2O. The relatively high conductivities were due to the presence of a porous zone of decomposed root channels which existed continuously in vertical direction. Besides decayed roots, living roots also encourage preferential flow in vertical and lateral (downslope) directions. Termite activities may also form water flow pathways in tropical regions. These detailed results help us analyze water flow within the soil in tropical rain forests.

Key words : decayed and living roots, preferential flow pathways, soil physical properties, termite activities, tropical rain forest

The high rate of deforestation in tropical regions has become a cause of concern (FAO, 1993). The deterioration and disappearance of tropical forests are frequently caused by social factors. There is a poor understanding about the hydrological functions of tropical rain forests, but there is concern about the effects of deforestation on overland flow and erosion. To solve problems of water resources and sedimentation, it is necessary to clarify the hydrological processes in tropical rain forests.

Many studies of soil in tropical forests have been conducted in southeast Asia (*e.g.*, Ohta, 1989; Ohta and Effendi, 1992; Takahashi *et al.*, 1994). However, most evaluated soil chemistry and nutrient cycling and there has been little detailed study of physical properties and water movement. Saturated hydraulic conductivity and soil-moisture characteristics are useful for analyzing water flow and slope stability (*e.g.*, Tsuboyama and Sammori, 1989; Sammori and Tsuboyama, 1990). Accordingly, it is necessary to collect these data in tropical forests to understand hydrological processes.

In this study we investigated the soil physical properties and water flow pathways in the soil of a tropical rain forest, Bukit Tarek in Peninsular Malaysia.

Materials and Methods

1 Site description

Bukit Tarek Experimental Watershed (BT) is located in Selangor Darul Ehsan in Peninsular Malaysia (latitude, 3° 31′ N; longitude, 101° 35′ E; altitude, 48-213 m; Fig. 1). The vegetation of this area is dominated by *Koompassia malaccencis, Eugenia* spp., and *Canarium* spp. Surficial geology is metamorphic rocks consisting of quartzite, quartz mica schist, graphitic schist, and phyllite from the Arenaceous Series (Saifuddin *et al.*, 1991). In the 3 years between 1992 and 1994, the air temperature ranged from 19.1℃ to 34.9℃ and the average annual precipitation was 2,414 mm. The minimum, maximum, and average mean monthly precipitation were 106.3 mm (January), 354.3 mm (November), and 221.2 mm, respectively. The monthly precipitation at BT had a bimodal distribution peaking in May and November. The rainfall was characterized by short duration and high intensity (Noguchi *et al.*, 1996).

2 Soil physical properties

Vertical undisturbed soil cores, 100 cm^2 in area and 4 cm deep (400 cm^3 in volume), were collected from the ridge (OR), upper slope (NR, DP) and lower slope (NS) at depths of 10, 20, 40, and 80 cm, respectively (Fig. 1). The saturated hydraulic conductivities (K_s) of these cores were measured using a constant head permeameter. The soil-moisture characteristics for these cores were determined by a sand column (for pressure head $\leq$ 31.6 cmH_2O) and a pressure chamber (for pressure head from 100 to 1,000 cmH_2O) experiments, respectively. The relationships between pressure head (ψ) and volumetric water content (θ) were analyzed by the van Genuchten equation (van Genuchten, 1980) as follows:

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{1}{1+(\alpha|\psi|)^n}\right)^{1-\frac{1}{n}} \quad (1)$$

where θ_s is the saturated soil-water content which was obtained experimentally, θ_r is the residual water content, and α and n are constants which were estimated from the retention data.

3 Investigation of water flow patterns in soil

Dye techniques allow the direct observation of patterns of water movement through soil profiles (*e.g.*, Bouma and Dekker, 1978; Tsujimura *et al.*, 1991). In this experiment, dilute solutions of methylene blue (0.03%) and white liquid

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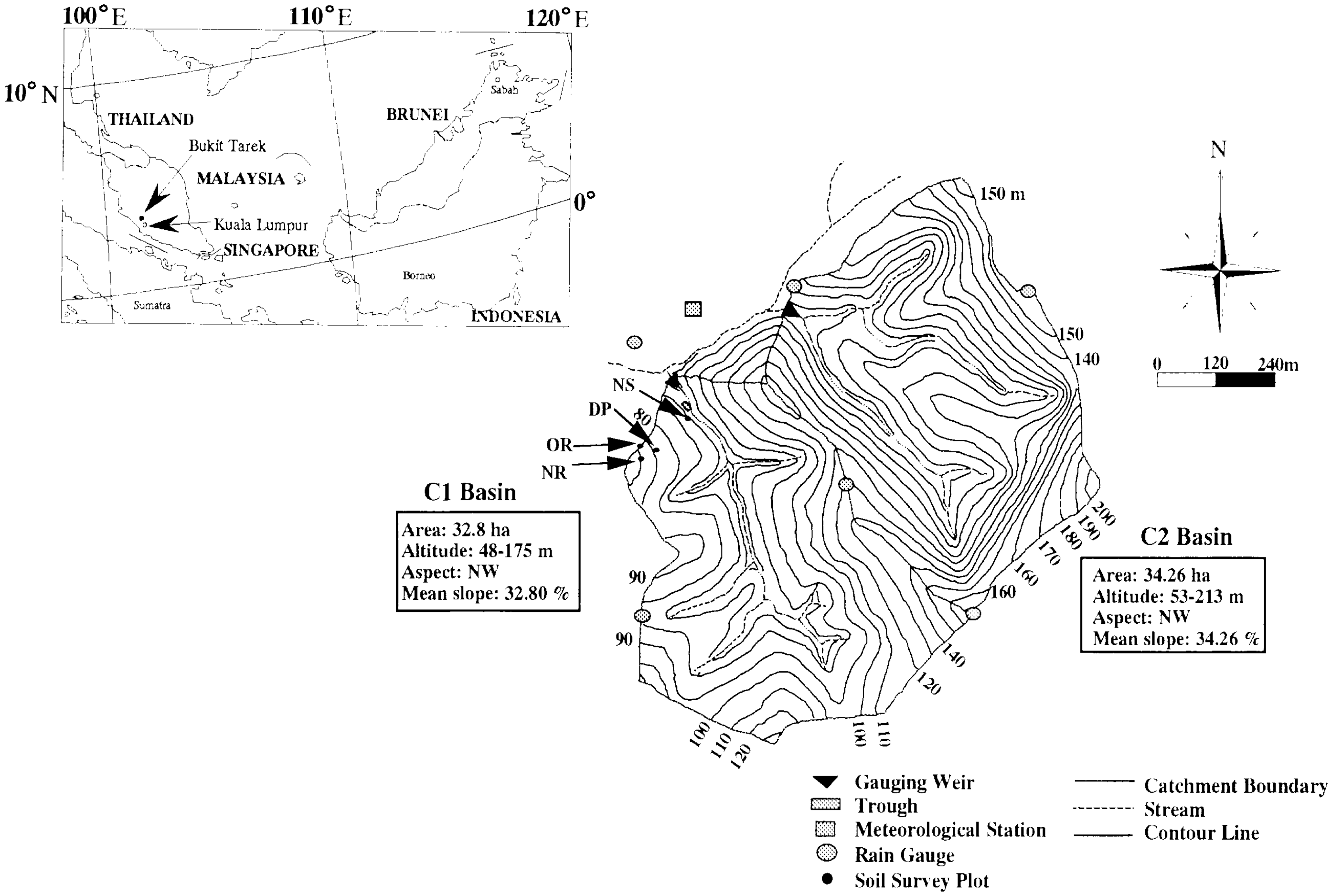

Fig. 1 Map of the Bukit Tarek Experimental Watershed showing the locations of the basins and their instrumentations.

paint (10% by volume) in water were used as a dye. Two plots (area: 1 × 0.5 m) were established at DP (Fig. 1) using wooden frames. The dyes (application rate: 80 mm h^{-1}; amount: 20 mm) were sprinkled on the plot after watering (application rate: 80 mm h^{-1}; amount: 40 mm). Twenty-four hours after applying the dye, the plots were trenched from the downslope end of the plot and the vertical distribution patterns of the dyes were described. The profiles were photographed and the stained dye patterns on the soil profile were traced. The pit face was cut at 10 cm increments, and the profile described for each face successively. The images were scanned in 256 colors and stored on computer. The color images were then converted to black and white images. An example of a soil profile dyed by white paint and its black and white image is shown in Fig. 6. The area of dye was calculated from the number of white pixels in the black and white images of each profile.

Results and Discussion

1 Soil physical properties

Generally, the decomposition of litter on a tropical rain forest floor is relatively rapid and the soil is poor in humus (*e.g.*, Whitmore, 1990). The organic-rich layer (A_0 and A layers) at this site was very thin. Sketches of soil profiles at OR, NR and NS are shown in Fig. 2.

Figure 3 shows the vertical K_s profiles and the geometric means at OR, NR and NS. The K_s values ranged from 6.40×10^{-4} to 7.51×10^{-2} cm s^{-1}. The K_s values decreased with increasing soil depth. Interestingly, one sample from each of the 40 and 80 cm depths at OR had a high conductivity. The K_s values at 40 and 80 cm, were 7.51×10^{-2} cm s^{-1} and 4.01×10^{-2} cm s^{-1}, respectively, and were larger than the geometric means at 10 and 20 cm depths. The high conductivities were due to porous zones which were predominantly caused by decomposed root channels and which existed continuously in a vertical direction (Fig. 2).

The geometric means of K_s values at BT were compared with K_s values from other tropical soils (Fig. 4). At all sites, the K_s values decreased with increasing soil depth, but the values varied by a factor of 10 at 10 cm depth and by more than 100 times below 40 cm depth. Such differences may alter the rainfall-runoff responses.

Some interesting hillslope hydrological studies have been undertaken in Australia (*e.g.*, Bonell, 1993; Bonell with Balek, 1993). The K_s values between 10–20 cm and below 20 cm depth at NC (North Creek in Australia) were 57 mm h^{-1} and 3.3 mm h^{-1}, respectively. Below 20 cm there was an impeding layer where saturated subsurface flow occurred during storms. Furthermore, infiltration-excess was possible in most storms because of the shallow impeding layer and high rainfall intensity. In contrast to this, the K_s values at BT were higher than those of other tropical soils at most depths

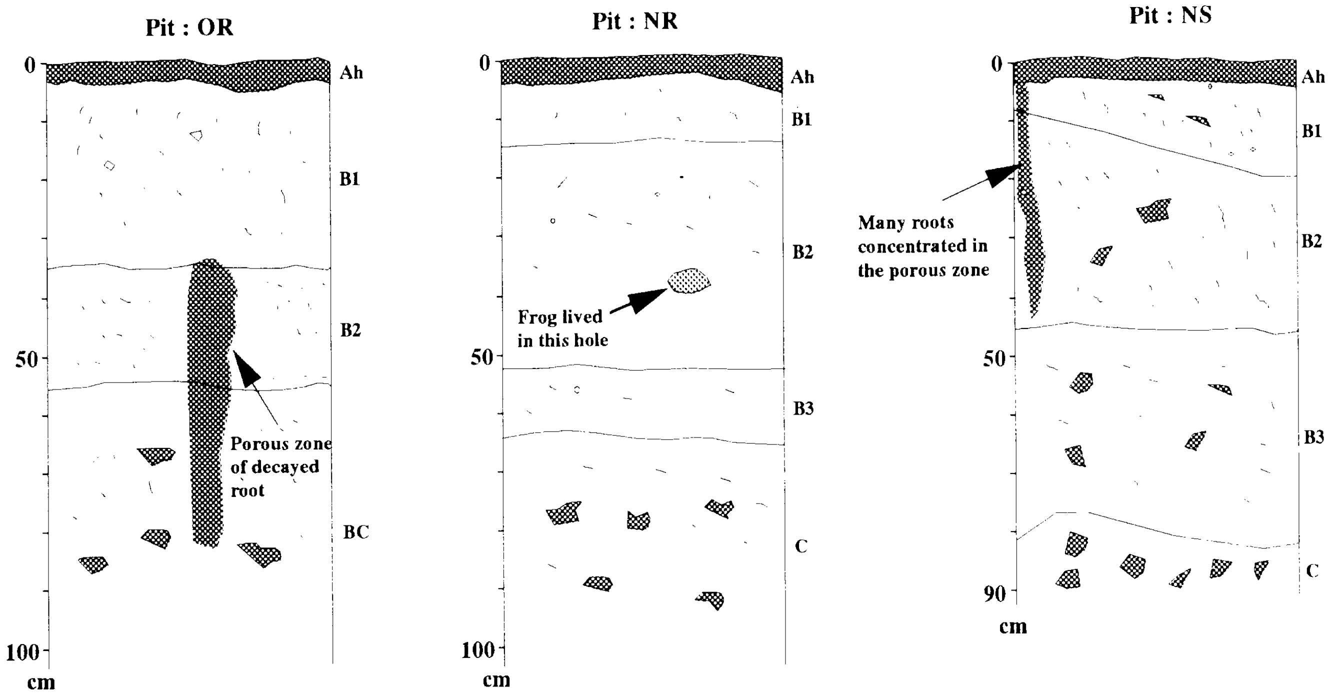

Fig. 2 Sketch and description of soil profile.

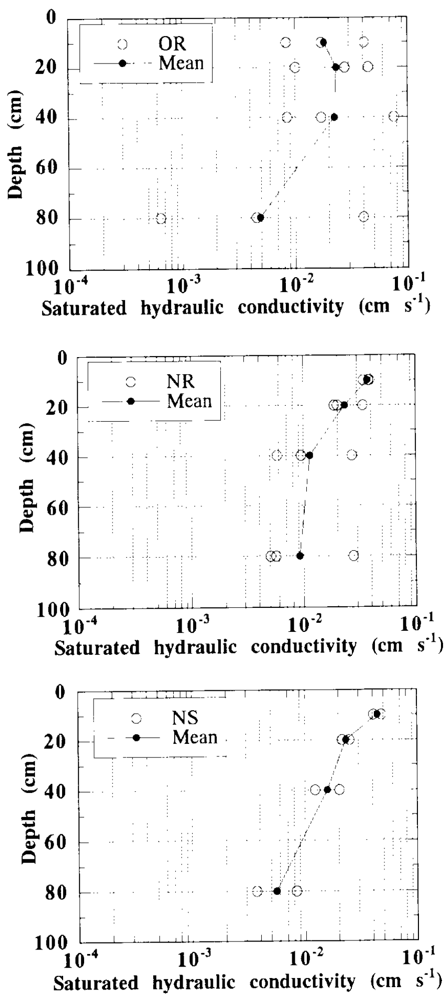

Fig. 3 The relationship between depth and saturated hydraulic conductivities (K_s) and the geometric mean.

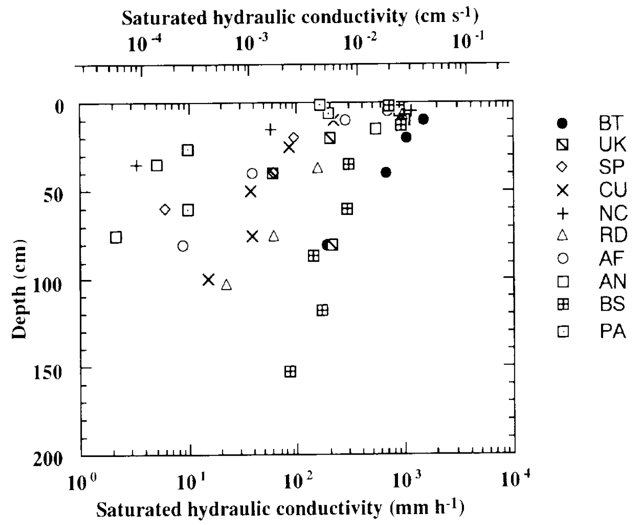

Fig. 4 The relationship between depth and saturated hydraulic conductivities in tropical regions. BT, Bukit Tarek in Malaysia; UK, Ulu Kalumpang in Malaysia (Source: Paul and Kuraji, 1993); SP, Sapulut in Malaysia (Source: Paul *et al.*, 1995); CU, Cunha in Brazil (Source: Fujieda, 1995); NC, North Creek in Australia (Source: Bonell, 1993); RD, Reserva Ducke in Brazil (Source: Nortcliff and Thornes, 1981); AF, Andulau Forest Reserve in Brunei (Source: Takahashi *et al.*, 1994); AN, Annandale in Grenada (Source: Ternan *et al.*, 1987); BS, Bukit Soeharto Conservation Forest in Indonesia (Source: Data provided by Ohta); PA, Pantabangan in Philippines (Source : Ohta, 1989).

(Fig. 4). The K_s values ranged from 1,466 mm h^{-1} at 10 cm depth to 169 mm h^{-1} at 80 cm depth. These K_s values are larger than the prevailing rainfall intensity at this site (Noguchi *et al.*, 1996). Therefore, saturation overland flow may not be dominant but subsurface flow must be important for generating stormflow. The high permeability of soils at this site could affect the runoff mechanisms on hillslopes.

The K_s values at BS (Bukit Soeharto in Indonesia) are similar to those of BT (Fig. 4). At BS, there are many mineral fragments and conspicuous coarse soil aggregates in the soil which could account for the high hydraulic conductivity through the profile (Ohta and Effendi, 1992). Further analysis, such as X-ray diffraction, is needed to clarify why the K_s

values at BT are higher than those of other tropical soils.

The relationships between pressure head (ψ) and volumetric water content (θ) described by curves fitted using Eq. (1) were determined for the soils of OR, NR and NS and are shown in Fig. 5. Kosugi (1994) found that the typical retention curve of forest soils shows changes in θ when $\psi <$ 30 cmH_2O. Although the $\theta-\psi$ curves of OR at 10 and 20 cm depth were a different shape from those of NR and NS, all the curves resembled a typical retention curve.

2 Characteristics of water flow patterns in soil

White liquid paint was useful but methylene blue was not effective for investigating the patterns of water flow in the soil, because most of it was absorbed in the organic-rich layer. After the white paint dye test, it was observed that the organic-rich layer outside the frame was dyed. This suggested that vertical percolation was deflected laterally between the organic-rich layer and the B layer. This was probably because the organic-rich layer was thin and had a very high density of roots and was therefore highly transmissive relative to the B layer. The rainfall at BT was characterized by high intensity (Noguchi *et al.*, 1996), and a perched water table might occur above the B layer during large storms.

The dye-flow patterns were uniform in the organic-rich layer but not in the B layer (Fig. 7b). The distribution patterns of the dye were not continuous vertically in the soil profiles

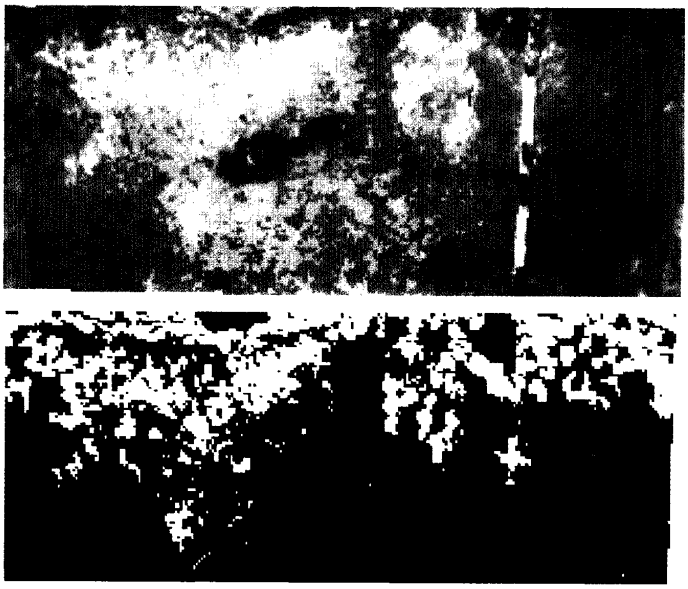

Fig. 6 Dyed soil profile converted to a black and white image.

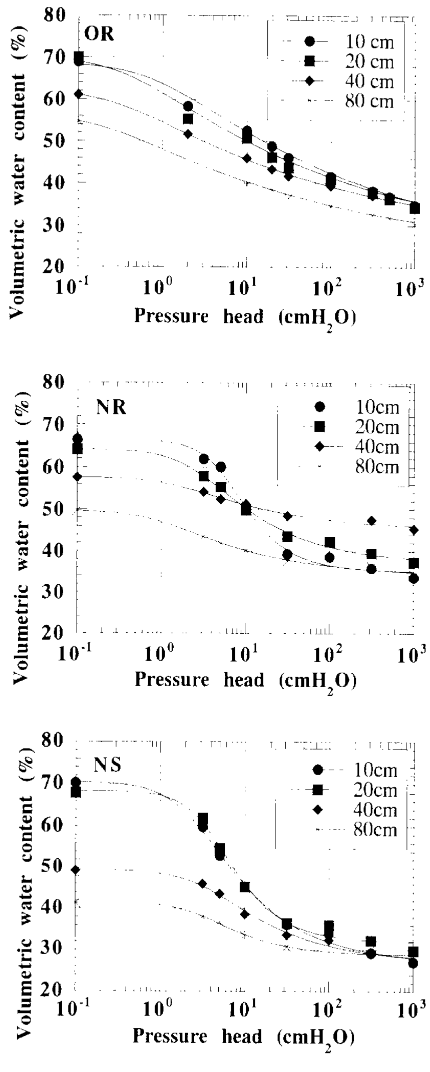

Fig. 5 Observed retention data and $\theta-\psi$ curves fitted using the van Genuchten equation.

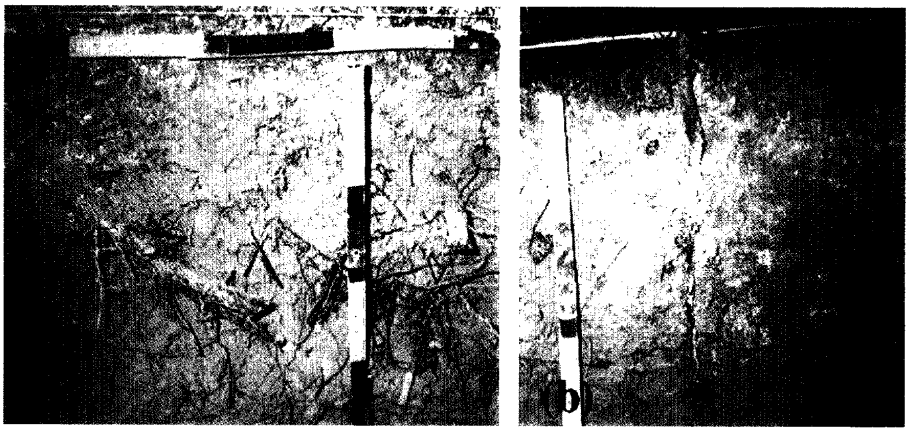

Fig. 7 The dye concentrated on living roots.
(a) lateral (downslope) direction, (b) vertical direction.

Fig. 8 Decayed root with termites and the dye stained around and inside t.

(Fig. 7). The areas covered by dye were 45-73 % at 0-10 cm depth, 20-67 % at 10-20 cm depth, and 2.5-14 % at 20-30 cm depth. The area covered by dye decreased with increasing soil depth in each soil profile.

Interestingly, the dye concentrated on decayed and living roots, especially, those which had developed vertically (Fig. 7b) or in a downslope (Fig. 7a) direction. Decayed roots provide channels which can act as pipes (*e.g.*, Tsukamoto *et al.*, 1988). Living roots may also affect the preferential flow paths. This is probably because living roots can impede flow locally and change the flow towards the soil around root which is non-compacted and highly conductive. In general, surface and shallow rooting habits are found in tropical rain forests. Lateral roots run beneath the soil surface at depth of 15-40 cm and can extend to 35 m from the stem (Baillie and Mamit, 1983). Such lateral root networks may play a more important role in distributing water in the soil of tropical rain forests than in temperate forests. Deep rooting habits in vertical direction can also be important. Baillie and Mamit (1983) found that the mean rooting depth in 32 trees was 2.35 m and that sinkers penetrated to depths of up to 4 m. These suggest that vertical rooting habits might also contribute to preferential flow in tropical rain forests.

Where there was a decayed root with termites in it, the dye stained around and inside it (Fig. 8). We found termite nests in the soil at three of the six sites we surveyed. The termite nest was softer than the soil around it. These areas might have different conductivity relative to the soil around them. In general, termites play an important role in the decomposition of dead wood and fallen leaves in tropical forests (Matsumoto, 1978). In addition, there are two contrasting theories on the effects of termites on water infiltration. One theory is that the termites repack the soil so that it forms a compact structure which reduces water infiltration, while the other theory considers that termites increase infiltration by incorporating organic matter into the soil and constructing galleries through the soil (Lobry and Conacher, 1990). A study on the hydro-geomorphological role of termites in Tanzania found that the underground tunnel network excavated by the termites in weathered bedrock might serve as a macro-pore to transmit or store groundwater (Matsumoto *et al.*, 1991). Termites are more widely distributed in tropical regions than in temperate regions (Abe and Matsumoto, 1978). Thus, termite activities may play an important role in the formation of water flow pathways in tropical regions.

Conclusions

Soil physical properties and water movement within soil were investigated using dye in a tropical rain forest, Bukit Tarek Experimental Watershed (BT) in Peninsular Malaysia. The following findings were obtained: (1) The geometric means of K_s values decreased with increasing soil depth. The K_s values at BT were higher than those of other tropical soils at all depths. The values differed between 10 times at 10 cm depth and over 100 times below 40 cm depth. The K_s values ranged from 4.69×10^{-3} (80 cm) to 4.07×10^{-2} cm s^{-1} (10 cm). This suggests saturation overland flow may not be dominant, but subsurface flow must play important roles in stormflow generation. (2) The shapes of the soil moisture characteristic curves at BT were typical of forest soils, and showed large changes in volumetric water content at pressure heads < 30 cmH_2O. (3) The dye test showed that vertical percolation was deflected laterally between the organic-rich soil and B layers. The relatively high conductivities of the soil were due to porous zones which were mostly decomposed root channels that existed continuously in vertical direction. Besides decayed roots, living roots also encourage preferential flow in vertical and lateral (downslope) directions. Termite activities may also form water flow pathways in tropical regions.

There are few research reports about the physical properties and subsurface flow characteristics of tropical forest soils. Therefore, these findings will provide useful information for analyzing water flow within soils in tropical rain forests.

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Appendix

Descriptions of surveyed soil profiles

Profile OR

Ah 0-3/5 cm; Dark brown (7.5YR3/4); loam; moderate medium granular and subangular blocky; common fine roots; very few mycelium; diffuse smooth boundary.

B1 3/5-35 cm; Brownish yellow (10YR6/6); light clay; weak fine blocky; very few faint humus cutanic features on pedfaces; few fine roots; very few mycelium; diffuse smooth boundary.

B2 35-55 cm; Brownish yellow (10YR6/6) and very pale brown (10YR7/4) mottling; light clay; weak blocky; few fine roots; very few mycelium and charcoal; diffuse smooth boundary.

BC 55-80+ cm; Reddish yellow (7.5YR6/8); clay; structureless; common weathered medium gravel; very few fine roots.

Profile NR

Ah 0-2/4 cm; Strong Brown (7.5YR4/6); silt loam; medium weak blocky and medium moderate granular; no rock fragment; common fine roots; very few mycelium; gradual smooth boundary.

B1 2/4-15 cm; Strong brown (7.5YR5/6); light clay; moderate coarse blocky; no rock fragment; very few medium interstitial voids; very few faint clay cutanic feature on pedfaces; few fine roots; diffuse smooth boundary.

B2 15-53 cm; Reddish yellow (7.5YR6/6); light clay; weak coarse blocky; very few medium channels; very few faint clay cutanic features on pedfaces; very few fine roots; difuse smooth boundary.

B3 53-65 cm; Reddish yellow (7.5YR6/6) with few fine distinct clear pink (7.5YR7/4) mottling; clay; very few medium interstitial voids and channels; very few faint clay cutanic features on pedfaces; very few very fine roots; clear smooth boundary.

C 65-100+ cm; Reddish yellow (7.5YR6/6); clay many subrounded weathered coarse gravel; few medium interstitial voids; very few very fine roots.

Profile NS

Ah 0-2/4 cm; Brown (7.5YR4/4); sandy clay; moderate medium granular and moderate fine blocky; very few subrounded weathered medium gravel; few fine roots; common ant nest; clear wave boundary.

B1 2/4-8/20 cm; Yellowish brown (10YR5/6); light clay; weak medium blocky; very few subrounded weathered medium gravel; very few medium root; diffuse wave boundary.

B2 8/20-45 cm; Strong brown (7.5YR5/6); clay; weak medium blocky; very few subrounded weathered medium gravel; few fine root; diffuse smooth boundary.

B3 45-83 cm; Strong brown (7.5YR5/6); clay structureless; very few subrounded weathered medium gravel; few fine roots; clear smooth boundary.

C 83-90+ cm; Strong brown (7.5YR5/7); clay; many subrounded strongly weathered coarse gravel structureless.