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Soil pipe distribution and hydrological functioning within the humid tropics: a synthesis

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Abstract:

Some of the most responsive runoff systems in the world are found within the humid tropics. These runoff responses are likely to be affected by the presence of *natural pipes* within the soil. This study provides a synthesis of the hydrological aspects of these phenomena within the humid tropics. Of the studies reporting the presence of soil piping within the humid tropics, most are associated with Ultisol soils, and, locally, most pipe outlets are observed on the lower sections of hillslopes. While the drainage role of pipes has been observed (providing faster and slower components of stream hydrographs), the mechanism of their recharge remains less clear. In part, this is because their spatial extent is poorly mapped within the hillslopes of the humid tropics. Further studies quantifying the length and recharge of soil pipe networks within the humid tropics are needed. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS Cicada burrow; humid tropics; preferential flow; soil pipe; Ultisol

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INTRODUCTION

The humid tropics cover one-fifth of the land surface of the globe (Figure 1 in Bonell and Balek, 1993; Chang and Lau, 1993). They extend from parts of Mexico to Brazil within the Americas, Senegal to Madagascar within the African domain and India to Northern Australia within the Indo-Malayan domain. The extent is similar to that covered by climate type 'A' of the Köppen-Geiger system (Peel *et al.*, 2007). This global region produces the greatest amount of runoff (Fekete *et al.*, 2002), and has headwater basins noted for their flashy rainfall–runoff responses (e.g. Bonell and Gilmour, 1978; Chappell *et al.*, 1999b; Dykes and Thornes, 2000; Godsey *et al.*, 2004). Furthermore, the region's catchments are subject to the greatest intensity of land cover disturbance through forest cutting (FAO, 2005). Despite the extent of this hydroclimatic region, its hydrological significance and the current pace of disturbance, there are relatively few studies addressing rainfall–runoff processes within humid tropical hillslopes and basins (Bonell, 2004; Chappell *et al.*, 2007).

Intensive research within experimental basins in temperate climates indicate that *natural soil piping* can be a dominant pathway for routing rainfall to rivers (Jones *et al.*, 1997; Uchida *et al.*, 1999; Jones and Connelly, 2002). These hydrological features can be defined as water conduits that are typically several centimetres or tens of centimetres in diameter and their networks can extend several metres or tens of metres within hillslopes. Their size and length make them a special type of macropore flow (cf. Jones, 1981, 1990; Scherrer *et al.*, 2007). Pipes can be enlarged by a combination of (a) sheer stresses exerted by flowing water on soil particles in pipe walls (a process formally called 'tunnel erosion'), and (b) by seepage forces within the soil that comprises pipe walls, which lead to Coulomb failure or liquefaction (so called 'true piping'; see Dunne, 1990; Bryan and Jones, 1997). In areas where piping is present, accurate simulation of subsurface flow within hillslopes may need the hydrological functioning of pipe systems to be parameterized explicitly (Jones and Connelly, 2002), or may necessitate modelling approaches alternative to those based on the Darcy–Richards Equation (Kirkby, 1988 p. 336). With much less experimental work on soil piping undertaken within the humid tropics (Bonell and Balek, 1993; Negishi *et al.*, 2007), their extent and hydrological role remains less clear. Studies such as Elsenbeer and Cassel (1990); Chappell *et al.* (1998); Elsenbeer and Vertessy (2000); Sayer *et al.* (2004); Chappell and Sherlock (2005) and Negishi *et al.* (2007) do, however, suggest that piping within humid tropical soils may have a significant impact on streamflow generation and the way that catchment models are parameterized and results interpreted.

Consequently, this study seeks to review and synthesize previous studies on soil piping within the humid tropics to consider: (i) the characteristics of their spatial distribution, (ii) their hydrological functioning, and (iii) key research needs. The review of published work is supplemented by further detailed observations from Danum (East Malaysia), the humid tropical location with possibly the greatest number of published pipe studies.

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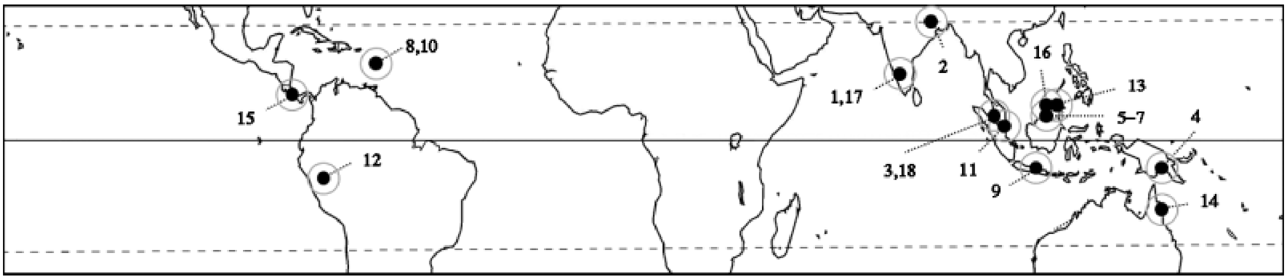

Figure 1. A map of the tropics (23·4 °N and 23·4 °S shown with broken lines) showing the distribution of published studies reporting soil pipe incidence within humid tropical regions. Names of the numbered locations are given in Table I

This study focuses on piping within soil in the strictest sense of the solum (i.e. A and B soil horizons). Within the humid tropics, piping has also been observed deep within underlying *regolith* in Sierra Leone (Dixey, 1920 p. 219; Thomas, 1968), Guinea (de Chételat, 1938), Guyana (McBeath and Barron, 1954 p97), Uganda (Patz, 1965), Columbia (Feininger, 1969), and Brazil (Bremer, 1973). However, detailed hydrological studies have not been undertaken on these, what might be called, *regolith pipes*. In addition, soil piping may be seen as having some of the preferential flow characteristics of rock fracture systems (Zhao, 1998) and karstic phenomena within rock (Gunn, 1986). These deeper strata (regolith and rock) are not examined within this review.

SPATIAL DISTRIBUTION OF PIPING WITHIN HUMID TROPICAL SOILS

The dearth of experimental studies on soil piping within humid tropical soils makes understanding their spatial distribution important for extrapolation of findings (however tentatively) and in designing and locating new experimental studies. Three questions arise when considering an initial assessment of their spatial distribution:

1. Do certain soil types found within the humid tropics have a greater reported incidence of soil piping?
2. Are the pipes of the humid tropics preferentially located with certain topographic locations?
3. Where within vertical profiles of humid tropical soils are pipes located?

Reported incidence of soil piping in humid tropical soils

If piping is primarily associated with specific soil types, then there may be underlying physicochemical reasons for this. As a result, the soil type associated with each reported incidence of piping within humid tropics is presented in Table I and Figure 1. The relatively limited number of studies presented within Table I shows that there are fewer studies than reported for soils within other global regions, particularly those within temperate or semi-arid climates (see e.g. the reviews of Jones, 1981, 1994; Jones *et al.*, 1997). The majority of studies in the humid tropics are reported for soils of the Ultisol order (Table I; Soil Survey Staff, 1999), though a few studies also report piping within Alfisol and Andisol soils (Banerjee, 1972; Walsh, 1980; Bruijnzeel, 1983; Walsh and Howells, 1988). Ultisol soils are equivalent to the former Acrisol group (FAO-UNESCO, 1974) and the Acrisol-Alisol groups of the current system (e.g. FAO-UNESCO, 1988). Acrisol is the dominant soil group of tropical Asia, and is particularly important within Malaysia, southern China, Cambodia, Vietnam, parts of Thailand and Indonesia (e.g. Sumatra and Sulawasi). Within tropical Africa it dominates only in southern Ghana and Côte D'Ivoire, and within South America, only within northern Venezuela and the south-western headwaters of the Amazon (FAO-UNESCO, 2007; Driessen *et al.*, 2001). Outside of the humid tropics, the Acrisol group dominates in Georgia, Alabama and the Carolinas in the south-eastern USA. Indeed, piping within Acrisol soils is reported within this humid sub-tropical region of the USA (e.g. Uchida *et al.*, 2005). Alisol soils are associated with Acrisol soils but can be distinguished by cation exchange capacities exceeding 24 cmol^{+} kg^{-1} clay (by 1 M NH$_4$O Ac at pH 7). For example, the piped soils at Danum, East Malaysia (Table I) are classified as a Haplic Alisol (Chappell *et al.*, 1999a). Globally, the Acrisol group is estimated to cover 1000 million hectares, while the Alisol group covers approximately 100 million hectares (Driessen *et al.*, 2001). This combined area is equivalent to more than twice the size of Southeast Asia.

The limited number of reported studies even for Ultisol soils could imply that such humid tropical soils, while being influenced by macroporosity (e.g. van Noordwijk *et al.*, 1991; Schwartz *et al.*, 1998; Reichenberger *et al.*, 2002; Ciglasch *et al.*, 2005), do not have extensive soil piping. Alternatively, the limited number of published studies may result from a wider dearth of research on runoff processes within the humid tropics and the difficulty of observing pipe outlets and depression lines within the region's dense rainforest cover. Indeed, subsurface flow within some hillslopes can be strongly influenced by soil piping despite the only visible evidence of piping arising during the excavation of soil pits (Sherlock, 1997; Lancaster, 1999; Chappell and Sherlock, 2005).

Ultisol soil within the humid tropics may be more sensitive to piping due to the strong decline of saturated

Table I. Location (see also Figure 1) and characteristics of pipes reported for soils in the humid tropics, ordered by date of first publication reporting piping at each location

Location	Soil type	Detailed pipe study (Y/N)	Diameter(s) (cm)	Length(s) (m)	Outlet density (per channel length or ha)	Flow measured (Y/N)	Reference
Majeedi (W Malaysia)-1	Ultisol	N	—	—	—	N	Burton (1964)
Lalgarth (India)-2	Alfisol	Y	1·0	—	—	N	Banerjee (1972)
Garbeta (India)-2	Alfisol	Y	10	—	—	N	Banerjee (1972)
Kuala Lumpur (W Malaysia)-3	Ultisol	N	—	—	—	N	Morgan (1973)
Mt Duau (Papua New Guinea)-4	Ultisol	Y	3–30	10–15	—	N	Löffler (1974)
Niah (E Malaysia)-5	Ultisol	Y	20	>30	—	N	Baillie (1975)
Bkt Mersing (E Malaysia)-6	Ultisol	Y	20	>30	—	N	Baillie (1975)
Segan (E Malaysia)-7	Ultisol	Y	15–25	>90	—	N	Baillie (1975)
Palmas (Dominica)-8	Andisol	Y	30	1·5	Limited	Y	Walsh (1980)
Kali Mondo (Indonesia)-9	Andisol	N	—	—	—	N	Bruijnzeel (1983)
Pointe Baptiste (Dominica)-10	Alfisol	Y	Mostly <10	—	29/500-m channel	Y	Walsh and Howells (1988)
Bkt Timah (Singapore)-11	Ultisol	N	2–8	—	—	N	Chatterjea (1989)
Bkt Timah (Singapore)-11	Ultisol	N	10	—	—	Y	Sherlock (1997)
La Cuenca (E Peru)-12	Ultisol	N	—	—	6/0·75 ha	Y	Elsenbeer and Cassel (1990)
La Cuenca (E Peru)-12	Ultisol	Y	5	—	6/0·75 ha	Y	Elsenbeer and Lack (1996)
La Cuenca (E Peru)-12	Ultisol	Y	—	—	6/0·75 ha	Y	Elsenbeer and Vertessy (2000)
Danum (E Malaysia)-13	Ultisol	N	5	—	—	N	Sinun (1991)
Danum (E Malaysia)-13	Ultisol	Y	1–10	—	—	N	Bidin (1995)
Danum (E Malaysia)-13	Ultisol	Y	—	—	—	Y	Chappell *et al.* (1998)
Danum (E Malaysia)-13	Ultisol	Y	14	>30	—	Y	Sayer (2002)
Danum (E Malaysia)-13	Ultisol	N	10–60	—	—	Y	Chappell *et al.* (2004a)
Danum (E Malaysia)-13	Ultisol	Y	—	—	—	Y	Chappell and Sherlock (2005)
Danum (E Malaysia)-13	Ultisol	Y	2–30	>30	—	Y	Sayer *et al.* (2006)
Babinda (NE Australia)-14	Ultisol	N	—	—	Limited	N	Bonell and Balek (1993)
La Selva (Costa Rica)-15	—	N	—	—	—	N	Parker (1994)
Belalong (Brunei)-16	Ultisol	N	10–15	—	—	N	Dykes and Thornes (2000)
Talakaveri (India)-17	Ultisol	Y	Several centimetre	—	—	Y	Putty and Prasad (2000)
Bkt Tarek (Malaysia)-18	Ultisol	Y	3·0–7·5	0·07–0·80	—	Y	Negishi *et al.* (2007)

The soil type utilizes Soil Survey Staff (1999); FAO-UNESCO (2007) and the references listed.

hydraulic conductivity (*Ks*) with depth and associated periodic water-logging (cf. Dunne, 1990 p. 22; Driessen *et al.*, 2001). In addition, Ultisol soils (particularly those equivalent to Alisol soils) are considered to be highly erodible (Driessen *et al.*, 2001; Dudal, 2005).

Outlet and upslope distribution of soil pipes in humid tropical basins

Several studies within the humid tropics report the location of *pipe outlets* (with visible water-flow or signs

Figure 2. Photographs of two pipe outlets: (a) a 5-cm diameter pipe outlet showing a water-level within the pipe just at the ground surface (pipe location is at 4°57·18′N, 117°48·12′E in the Danum area, East Malaysia), and (b) the emergence of a tracer slug (1 : 10 diluted, white emulsion paint) from a pipe outlet after its input to a former cicada burrow, 10-m upslope (see Figure 3b)

that it has taken place recently). Most pipe outlets in the humid tropics are observed on the lower sections of hillslopes, close to ephemeral or perennial stream channels (Burton, 1964; Banerjee, 1972; Löffler, 1974; Baillie, 1975; Walsh, 1988; Bruijnzeel, 1983; Walsh and Howells, 1980; Sayer, 2002; Sayer *et al.*, 2006; Putty and Prasad, 2000; Negishi *et al.*, 2007). From theoretical considerations (e.g. Terzaghi and Peck, 1948; Dunne, 1990; Jones, 1990), areas of a hillslope with greater seepage forces are more likely to generate pipes. Hillslope areas with greater seepage forces are likely to be downslope areas and areas of subsurface flow convergence—perhaps formed by depressions in the rock-head and its impact on the topography of overlying soil horizons. Once a pipe develops in an area of subsurface convergence, then drainage of this area would be increased and thereby further increase the degree of convergence to this area in a positive feedback (cf. theory of formation of solution dolines: Williams, 1985). The exact location of pipes within these zones of subsurface convergence is then likely to be a function of the local spatial variability in the saturated hydraulic conductivity, *Ks* (Dunne, 1990 p. 29; Vieira and Fernandes, 2004).

Within downslope areas of studied slopes in the humid tropics, the outlets can be: (i) an upwelling on the floor of the hillslope concavities or shallow side slopes (Figure 2a), (ii) a hole in the vertical headwall of small seeps (e.g. Elsenbeer and Lack, 1996), or (iii) a hole in the head or wall of incised channels (e.g. Löffler, 1974; Baillie, 1975; Walsh and Howells, 1988; Sayer, 2002; Sayer *et al.*, 2006; Negishi *et al.*, 2007). Indeed, some of the incised, ephemeral channels in the humid tropics are reported to be forming through: (1) retreat of headwalls accelerated by Coulomb failure and soil fall at pipe outlets (Löffler, 1974; Bidin, 1995), and/or (2) collapse of short sections of pipe roof (Burton, 1964; Baillie, 1975; Sayer, 2002). Pipe outlets can be found on the lower sections of hillslopes both at the head of permanent stream channels (e.g. Negishi *et al.*, 2007) and on the sideslopes of permanent stream channels (e.g. Baillie, 1975; Walsh and Howells, 1988). In addition, within the Danum area of East Malaysia, 5 to 15-cm diameter pipe outlets can be observed to discharge water intermittently from the lower sideslopes of second- and third-order permanent channels (e.g. at 4°58·39′N, 117°48·98′E and 4°57·61′N, 117°48·17′E; Figure 2b) but also through the bed of these permanent channels (e.g. at 4°57·93′N, 117°48·00′E).

While active pipe outlets are easily recognizable by their visible resurgence of water during rain-events (particularly during intense rain-events), the *upslope extent* of soil pipes is difficult to identify within soils of the humid tropics (Walsh and Howells, 1988; Negishi *et al.*, 2007). Table I shows that data on the upslope extent is rarely measured and reported within piping studies in the humid tropics. Löffler (1974); Sayer *et al.* (2006) and Baillie (1975) do, however, report pipes extending 15, 30, and 90 m within hillslopes, respectively. Pipes exposed by intermittent collapses are more readily identified. Figure 3 shows such a pipe at Segan (redrawn from Baillie, 1975) and at Danum (i.e. 'PT trail pipe' at 4°57·68′N, 117°48·15′E, redrawn from a survey by A. Freer) both in East Malaysia.

Further evidence for the presence of soil pipes extending away from near-channel outlets has come from their observation within man-made soil pits (Sinun, 1991; Elsenbeer and Lack, 1996; Sherlock, 1997) and slope cuts (Morgan, 1973; Parker, 1994; Putty and Prasad, 2000). However, with such data, only the presence of pipes within upslope areas can be established, not their length.

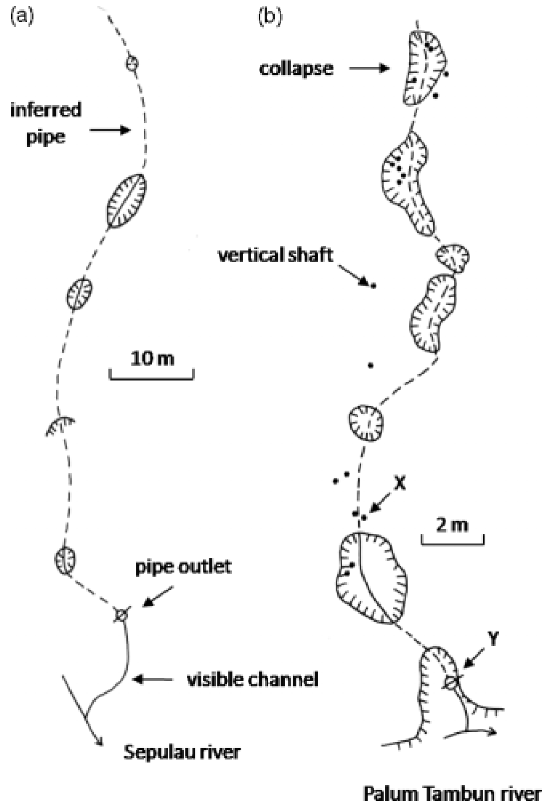

Figure 3. Lateral pipe cum gully systems at: (a) Segan, East Malaysia (redrawn from Baillie, 1975) and (b) the Palum Tambun trail area of Danum, East Malaysia (4°57·68′N, 117°48·15′E; redrawn from a survey by A. Freer). Former cicada burrow X is shown to be connected hydrologically to the river-bank outlet (Y) during the tracer test illustrated in Figure 2b

Better experimental evidence for pipe length comes from observations at Danum. Here flowing pipe outlets in gully sidewalls are sometimes associated with a very shallow (<10-cm relief) linear depression extending away from the pipe outlet in the gully (e.g. pipe outlet 'B' in Figure 3 of Sayer, 2002). Recently, artificial addition of tracer (namely 1 : 10 diluted, emulsion paint of various colours) into several 3-cm diameter natural shafts (probably former cicada burrows) along the line of this pipe depression (at up to 10 m from the pipe outlet) was visible within minutes to tens of minutes at the outlet (personal observation). Such tracer tests showing upslope extent of individual pipes (and the connectivity with some former cicada burrows) have been undertaken on other pipes in the Danum area. Figure 2b shows emergence of a tracer slug from a pipe outlet (marked with a 'Y' in Figure 3b) after its input to a former cicada burrow, in this case 10-m upslope (marked with an 'X' in Figure 3b).

Other evidence for the presence of pipes extending away from channel areas may come from the behaviour of soil moisture probes. Figure 4 shows a time series of soil moisture content measured at 0·50-m depth on a steep slope section at 4°58·52′N, 117°49·03′E (Danum, East Malaysia). After installation, it was noticed that the profile of soil moisture measurements at this location was immediately downslope of a shallow linear depression that extends up towards the hillslope divide. The marked bimodal recessions shown in Figure 4 (with upper sections drying just as quickly as the soil wetted) may indicate that the soil at this depth is being saturated by a soil pipe beneath the depression during storm events. This unusual behaviour was not noted at other moisture measured profiles throughout the Baru basin (Suhaimi, in prep). This hillslope was also subject to an earlier tracer test using a steady-state application of water (followed by pulse of technicium-99m tracer). Water was applied to a trench upslope of the same linear depression, and at e.g. 19 m further downslope (in riparian piezometer No. 4) the peak in the water breakthrough curve was attained after only 185 min. Following the analysis of Radulovich *et al.* (1989), this rapid water migration would be consistent with the presence of a preferential pathway such as a pipe system, as inferred from the moisture dynamics.

Negishi *et al.* (2007) attempted to measure pipe lengths by inserting a straight stick into several pipe outlets at their Bukit Tarek site in West Malaysia. They were only able to insert the stick up to 80 cm from the outlet. Given that individual pipes can follow a tortuous route (see e.g. Figure 2a, b), insertion of straight stick will be soon stopped even where a pipe extends over many metres. Indeed, the general lack of measurements of pipe length within studies in the humid tropics (Table I) is no basis for assuming that individual pipes do not extend beyond the few tens of centimetres visible by looking into an outlet.

From personal observation, it should be emphasized that some flowing outlets near ephemeral or perennial streams are not associated with either a line of pipe collapses or a shallow linear depression upslope of the outlet (e.g. at 4°58·39′N, 117°48·98′E). In these circumstances, establishing pipe length would certainly require the progressive excavation of the whole hillslope or monitoring pipe outlets for tracers applied to upslope sections of pipe (Smart and Wilson, 1984; Anderson *et al.*, 2008). Indeed, these approaches would be beneficial on all humid tropical hillslopes with evidence of piping. Only with observations of: (i) lines of pipe collapses (Baillie, 1974), (ii) whole hillslope excavations (Anderson *et al.*, 2008) or (iii) tracing along pipe sections (Smart and Wilson, 1984) can the typical, upslope extent of piping be quantified in the humid tropics.

Location of lateral pipes within soil profiles in humid tropical basins

Within the humid tropics, the solum (or A and B soil horizons) of Ultisol soils can range from <0·5 m to >1·5-m deep (e.g. Acres *et al.*, 1975). Lateral soil pipes exposed by gully incision, soil pit excavation or slope cutting during road construction are found at any depth within this range and several pipes at different depths can be present in the same exposure of a soil profile (Bidin, 1995; Negishi *et al.*, 2007; Figure 5). As noted earlier, pipes also may be present in the regolith below the solum.

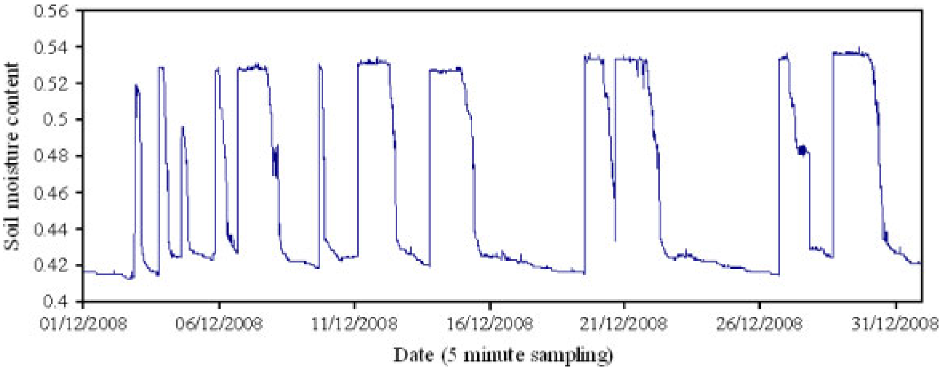

Figure 4. A time series of volumetric moisture content ($cm^3\ cm^{-3}$) monitored at 0·5-m depth and immediately downslope of a shallow (<10-cm relief) linear depression (at 4°58·52′N, 117°49·03′E within the 2M Baru basin, Danum, East Malaysia). This depression extends up towards the hillslope divide. The marked bimodal recessions, with upper sections drying as quickly as the soil wetted, may indicate that the soil matrix at this depth is being saturated by a lateral pipe during storm events. This behaviour was not noted at other moisture measurement profiles throughout the Baru basin (Suhaimi, in prep). The soil moisture values at the measurement profiles were observed using Campbell Scientific Ltd CS616 probes and automatically recorded every 5 min using a CR1000 data-logger

At Niah (East Malaysia), the greatest depth in the soil profile where pipes have been recorded is 1·5 m (Baillie, 1975), at Pointe Baptiste, Dominica, it is 1·3 m (Walsh and Howells, 1988), at Bukit Tarek, West Malaysia, 1·5 m (Negishi *et al.*, 2007) and at Danum, East Malaysia, 1·4 m (Figure 5a). For example, Figure 5a shows the location of active, lateral pipes (with evidence of water-flow) within a 1·5-m high gully sidewall (4°57·18′N, 117°48·12′E), while Figure 5b shows them within a gully head 5 km away (redrawn from Bidin, 1995). The locations of small macropores only ca. 0·5 to 1-cm diameter are also shown within Figure 5a, b, but it is not known which of these regularly conduct significant amounts of water-flow (i.e. 'hydrologically active macropores') and which of the faunal burrows (associated with worms, termites etc.) rarely conduct water. Within gully walls that contain active lateral pipes at several levels, the largest pipes tend to be at the base of the gully wall (e.g. Figure 5a, b). The same pipes also tend to flow more frequently (personal observation at Danum).

Three factors may affect the location of lateral pipes at one or more depths within Ultisol soil profiles within the humid tropics. These factors are vertical changes in: (i) *Ks*, (ii) soil erodibility, and (iii) proximity to the local water-table.

1. *Saturated hydraulic conductivity (Ks) reduction with depth:* Research outside of the tropics has shown that large lateral pipes are often found immediately above layers of reduced *Ks* (Yasuhara, 1980; Jones, 1981 p81). As soils within the humid tropics often exhibit a predominantly monotonic decline of *Ks* with depth (Chappell and Ternan, 1992; Elsenbeer, 2001; Chappell and Sherlock, 2005), a lower *Ks* in the strata immediately below a lateral pipe is likely. Figure 6 shows the vertical distribution of *Ks* of soil profiles containing piping at La Cuenca (Elsenbeer and Lack, 1996; Elsenbeer and Vertessy, 2000), Bukit Tarek (Ziegler *et al.*, 2006) and Danum (Chappell *et al.*, 1998).
2. *Local increases in erodibility of piped strata:* Aggregate stability has been shown to be lower within piped soil horizons within temperate and semi-arid climates (Beckedahl, 1977; Jones, 1981). Such data are extremely limited for piped soils in the humid tropics. A small number of aggregate stability tests were, however, undertaken on a soil layer with active piping and on adjacent layers at one location in the Danum area (Chappell *et al.*, 1999a). The piped layer at 0·94-m depth (in a profile surveyed by Bidin, 1995; Figure 5b) had a lower aggregate stability (i.e. 60%) compared to higher strata (i.e. 77–100%).

Exchangeable Sodium Percentage (ESP) is inversely correlated with aggregate stability within some soil types (Goldberg *et al.*, 1988). Within Alfisol soils of dry tropical Zimbabwe, Stocking (1981) observed that soil horizons with pipes have a higher ESP compared to non-piped horizons. The study of Chappell *et al.* (1999a) conducted within the humid tropics, demonstrated a similar relationship, with an ESP of 7·43% for the piped layer, compared to 2·58–4·14% for the layers higher in the profile.

3. *Changing likelihood of water-flow in lateral pipes with depth:* Walsh and Howells (1988), Bidin (1995) and Figure 5a show that where lateral pipes at several levels are exposed by gully incision, the larger pipes that also flow more frequently, tend to be located at the base of channel banks. In some contrast, the study of Negishi *et al.* (2007) showed that while flow was correlated with the size of pipe outlet, neither was correlated with depth at their studied gully head in West Malaysia.

Tracer application at Danum (e.g. at pipes shown in Figure 5a and shown in Figure 3 of Sayer, 2002) would indicate that multilevel, lateral pipes may be connected. Where this is the case, it is expected that the deeper, lateral pipes would maintain local saturation or free-surface flow for longer (with higher pipes draining into

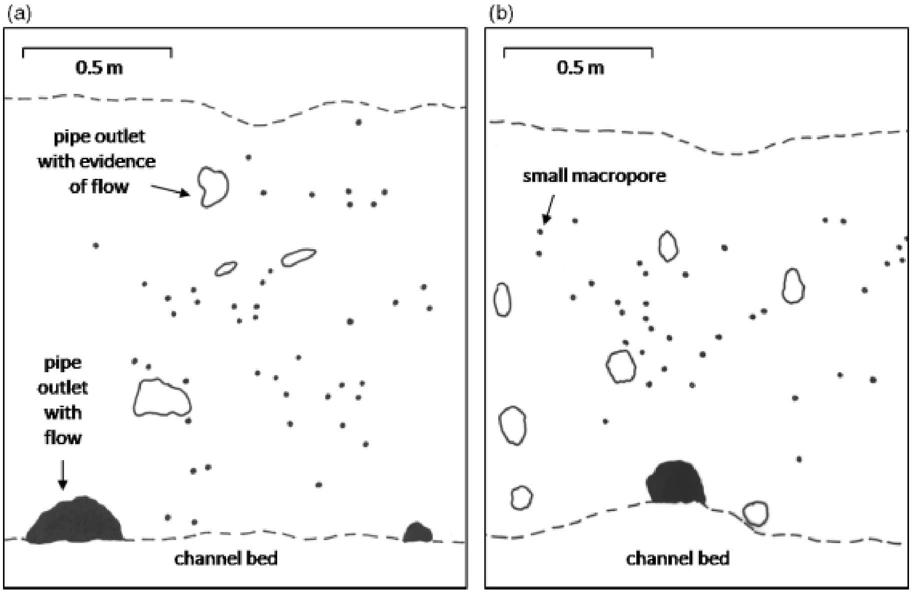

Figure 5. Soil profiles along incised gullies that contain small macropores (which may or may not transmit water) and soil pipes either with observed flow or with evidence of previous flow. Survey (a) is of a gully sidewall at 4°57·18′N, 117°48·12′E (redrawn from a survey by A Freer), and (b) a nearby gully head (redrawn from Bidin, 1995)

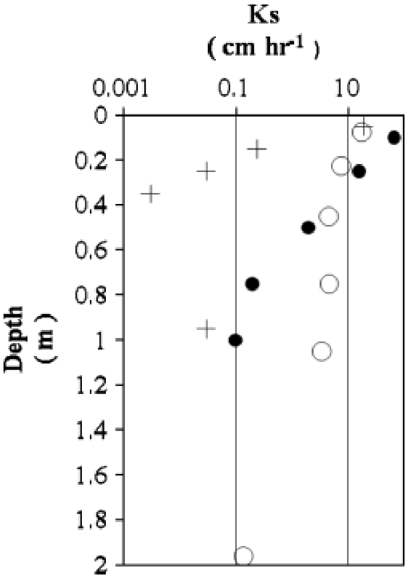

Figure 6. The median value of saturated hydraulic conductivity (*Ks*) at each depth in the soil profile representative of three locations with soil piping, namely: (i) La Cuenca, Peru (crosses; data from Elsenbeer and Lack, 1996 and Elsenbeer and Vertessy, 2000), (ii) Bukit Tarek, West Malaysia (closed circles; data from Ziegler *et al.*, 2006) and (iii) Danum, East Malaysia (open circles; data from Figure 4a in Chappell *et al.*, 1998)

these; cf. Jones and Connelly, 2002). With more water-flow, greater pipe enlargement would be expected, so making these pipes larger. Consequently, there may be a two-way relation between the local pipe distribution and hydrological functioning at some humid tropical sites.

Vertical pipes and cicada burrows

Cicadas, insects mostly of the family Cicadidae, when newly born as nymphs, excavate vertical burrows within humid tropical soils. After living on roots for 2–5 years, they emerge from the surface via 8 to 14-cm high domed 'chimneys' (Lander, 1895; Sinun, 1991). These chimneys erode away within a few months (Sinun, 1991), to leave an exposed vertical shaft some 3 cm in diameter. Some cicada burrows remain as isolated, dry shafts, e.g. the 60-cm deep vertical shaft shown in Figure 7 that was filled with Plaster of Paris (calcium sulphate hemihydrates, $CaSO_4H_2O$) and then excavated. Other cicada shafts have been shown to connect to large, lateral pipes. For example, cicada burrow marked with an 'X' in Figure 3b has been confirmed (using a diluted emulsion paint tracer) to connect to a large lateral pipe. Other cicada burrows have been shown to connect to lateral pipe networks by attempting, but failing to fill the burrows with a 6 l/s water pump (in a soil where the *Ks* reduces to <10 cm/hr at 0·45-cm depth; Figure 6c). Furthermore, in some downslope locations within the Danum area, water has been seen to spout from such holes during rain-events; holes, which look like the holes found in hillslope areas containing clusters of many cicada chimneys (personal observation). Where lateral pipe-flow erodes a connection with a vertical cicada 'shaft', and the piezometric surface (within the pipe system) goes above the local ground surface, pipe flow would be expected to emerge from the ground via these former cicada burrows. The pipe outlet shown in Figure 2a may have once been a cicada 'shaft'. Where such vertical cicada 'shafts' have such hydrological connections with the large lateral pipes they should be considered as part of the pipe system.

A repeat survey of cicada 'chimneys' in six 20 m^2 plots at Danum by Sinun (1991) showed densities of 15 chimneys per m^2. Thus, density was as high as the 14 chimneys per m^2 found by the seminal study of Scully (1942) at sites within the USA. Given that cicadas are present throughout the humid tropics, the possibility that the vertical shafts that they create could act as outlets for pipe flow requires further investigation.

Figure 7. A vertical cicada burrow filled with Plaster of Paris and then excavated (undertaken by V. Grimsey). The shaft extends to a depth of 60 cm (undisturbed soil is observed beneath), and is located only 20 cm from the bank of a gully formed by pipe collapse (4°57·68′N, 117°48·15′E; Figure 3b). The shaft diameter is mostly between 2 and 3 cm. The top 10-cm section of the shaft has been removed and is not visible in the photograph

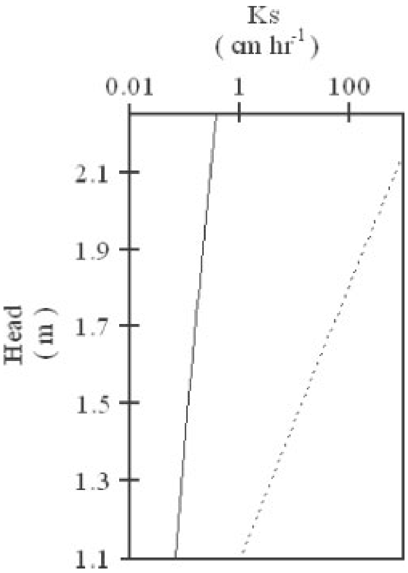

Figure 8. Lateral saturated hydraulic conductivity of the soil profile at Danum, East Malaysia after core-based permeametry values have been up-scaled (solid line), together with the *effective lateral Ks* values derived from inversion of a catchment model (broken line; data from Chappell *et al*., 1998). The latter includes the effects of soil piping on catchment-scale runoff generation, and only minimal overland flow

Effect of hillslope disturbance on piping within the humid tropics

In the humid tropics, where forestry roads have been built across ephemeral stream channels without the incorporation of a drainage conduit (typically a hollow log culvert) new pipes can sometimes be observed to develop through the fill materials (personal observation, e.g. at 4°58·51′N, 117°49·14′E). However, there are no published studies for the humid tropics that have examined how such soil and hillslope disturbances may affect the incidence or hydrological functioning of such soil pipes, as was studied by Ziemer (1992) within a temperate region of the USA. This contrasts with the number of studies quantifying the loss of small macropores resulting from tropical rainforest disturbance (e.g. Spaans *et al*., 1989; Balbino *et al*., 2004; Schack-Kirchner *et al*., 2007).

HYDROLOGICAL FUNCTIONING OF PIPES WITHIN HUMID TROPICAL SOILS

Lateral soil pipes within the humid tropics are an extreme form of preferential flow that can focus the drainage and subsequent outflow of a significant proportion of hillslope water (Löffler, 1974). At this hillslope scale, we might consider a continuum of increasing preferential flow from topographic convergence to topographic convergence with a *percoline* (i.e. linear zone of high *Ks*: Bunting, 1961) to a long lateral pipe. Within some instrumented microbasins in the humid tropics, a significant proportion of the streamflow generation can come via lateral soil pipes (Sayer *et al*., 2004). The study of Putty and Prasad (2000) states25%, Walsh and Howells (1988) state >20%, Negishi *et al*. (2007) state 48% from several pipes at the channel head, while Sayer *et al*. (2004, 2006) show up to 47% from a single pipe resurgence.

Impact of lateral pipes on effective Ks of humid tropical hillslopes

Considering the hillslope as a hydrological unit, the presence of large, lateral pipes within the soil will increase the *effective, lateral saturated hydraulic conductivity* of the soil profile. Figure 8 shows the measured *Ks* of the Danum soil profile after being up-scaled to a *lateral Ks* value (adapted from Chappell *et al*., 1998, 2004b). The broken line in the same figure shows the *effective lateral Ks* values derived from inversion of a catchment model (TOPMODEL) applied to rainfall–runoff data from the Baru catchment (similarly adapted from Chappell *et al*., 1998, 2004b). The latter implicitly includes the dominant runoff pathways (thus, potentially, the effects of soil piping) on catchment-scale runoff generation. Studies undertaken outside of the tropics (e.g. Brooks *et al*., 2004) show a similar magnitude of difference between the *Ks* for a hillslope profile derived from measurements at a point (e.g. core-based or auger hole-based tests) and those inverted from the whole hillslope or catchment behaviour. For hillslopes containing these extreme preferential pathways, the actual patterns of subsurface flow may bear little relation to those indicated by small core-based (or auger hole-based) *Ks* tests. Rather than flow responding to the patterns in *Ks* linked to tropical soil horizons (Elsenbeer, 2001) or a tropical soil catena (Chappell and Ternan, 1992), patterns may be overwhelmingly a function of the spatial distribution of the lateral pipes network

(Kirkby, 1988; Bonell and Balek, 1993, p. 198; Bonell, 2004 p. 317). Indeed, the tropical tracer study of Chappell and Sherlock (2005) provides evidence that this may be the case with subsurface flow direction being little related to the vertical distribution of core-based *Ks* values.

Comparison of soil pipe outlet and stream time constants within humid tropical basins

Time series' of water discharge emerging from lateral soil pipes have been measured at several experimental sites within the humid tropics (Walsh and Howells, 1988; Sayer *et al.*, 2004, 2006; Negishi *et al.*, 2007). At other sites within the humid tropics, surface flows have been gauged a few metres downslope of pipe outlets (Elsenbeer and Lack, 1996; Elsenbeer and Vertessy, 2000; Putty and Prasad, 2000; Sayer *et al.*, 2004, 2006). The studies of Sayer *et al.* (2004) and Negishi *et al.* (2007) allow comparison of flow in an ephemeral stream channel with that proportion generated by the resurgence of pipe flow. The flow observed within the channels will be a mix of pipe flow, exfiltration of water from the soil matrix (including flow through small macropores), and precipitation falling onto the locally saturated soil. The gauged pipes in both the Negishi *et al.* (2007) and Sayer *et al.* (2004) studies cease flowing several hours after rainfall. The hydrograph recessions for the gauged pipes in these two studies can be faster than that of flow within the ephemeral stream channel (see e.g. pipe 3 in Figure 6 of Negishi *et al.*, 2007) or indeed slower (see e.g. W3 pipe in Figure 1 in Sayer *et al.*, 2004). Figure 9 shows an 11-day period of discharge gauged at the outlet of the W3 pipe, and at 30-m downstream in the ephemeral stream channel. The difference in the rate of recession and hence time constant of the response is apparent, with the pipe having longer recessions. The nearby gauged W8S5 third-order stream (4°57·68′N, 117°47·66′E) also has faster hydrograph recessions in comparison to the W3 pipe. The W8S5 stream has a time constant, TC (determined by a first-order transfer function, with or without a non-linear transform: Chappell *et al.*, 1999b) of approximately 1 h and hence is comparable to that of the nearby Baru stream (Chappell *et al.*, 1999b). In contrast, the W3 pipe has a time constant of approximately 40 h. The time constants relate to the slope of the recession of output (i.e. pipe flow or channel flow) relative to that of the input (i.e. hyetograph). The longer time constant for the W3 pipe outlet (gauging an area of <1 ha: Sayer *et al.*, 2006) implies that the dominant water pathway to this outlet is significantly slower than that of the 1·5 km^2 W8S5 basin, or indeed of the 1·32 ha microbasin gauged only 30-m downstream of the pipe outlet.

Faster paths observed in the streamflow records could be related to (i) saturated ground, (ii) a dominance of hillslopes shorter than those with extensive pipe systems, or (iii) lateral pipes higher within the soil profile that have a more flashy flow regime. Local observations of these three factors are available:

1. Only a small proportion of the streamside soils within the W8S5 or Baru basins are saturated (i.e. from moisture measurements at 1197 points within 10 m of all perennial channel within the Baru, less than 10% are more than 95% saturated: S. Abu Bakar, personal communication).
2. As the resistance to flow within a large soil pipe is considerably less than the resistance to flow expected through the matrix (or even fine macropores) of the silt loam soil (Chappell *et al.*, 1999a), the slower response is more likely to relate to the mechanism of recharge of the W3 pipe. The W3 pipe basin has an elongated headwater area, which extents to more than 60-m upslope of the pipe outlet (see Figure 2 in Sayer *et al.*, 2006). Such basin shape effects can damp the delivery of water towards a main pipe (or stream; see Bras, 1990 p. 397).
3. An 8-cm diameter pipe which supplies all of the flow to weir E6 in the Baru catchment (and then drains into a 60-cm diameter pipe: Chappell *et al.*, 2004a) has a time constant of approximately 1 h and hence is comparable to that of the third-order Baru stream (or W8S5 stream). This pipe outlet only produces flow irregularly and is located towards the top of the gully head at a height of 1·2 m. This contrasts with the W3 pipe of Sayer *et al.* (2004) with its slower time constant, which discharges close to the base of the gully head, and hence close to the level which is regularly saturated (i.e. the local water-table along the channel: see Bidin *et al.*, 1993; Chappell *et al.*, 2006). Indeed, visual observations would suggest that the pipe above weir E6 may be discharging water on to an initially dry channel, as noticed by Putty and Prasad (2000) at monitored sites in India.

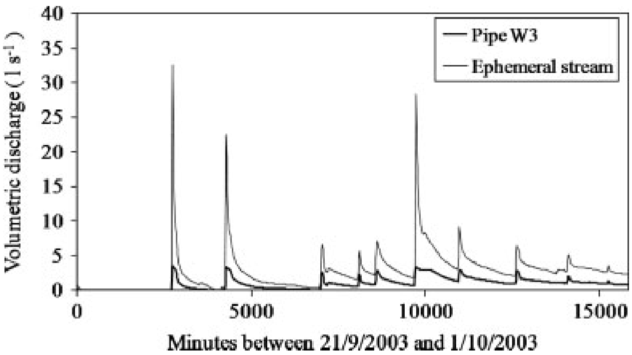

Figure 9. A 11-day time series of discharge gauged at the outlet of the W3 pipe, and 30-m downstream in the ephemeral channel (data collected by A Sayer and J Hanapi)

The gauged pipe within the 0·75 ha La Cuenca basin (East Peru) has an even shorter time constant of only a few minutes (Elsenbeer and Vertessy, 2000). This pipe outlet is less than 10 m from an ephemeral stream channel, but is 16 m above the height of the perennial stream ('P1' in Figure 3 of Elsenbeer and Vertessy, 2000), and hence the 'permanent' water-table.

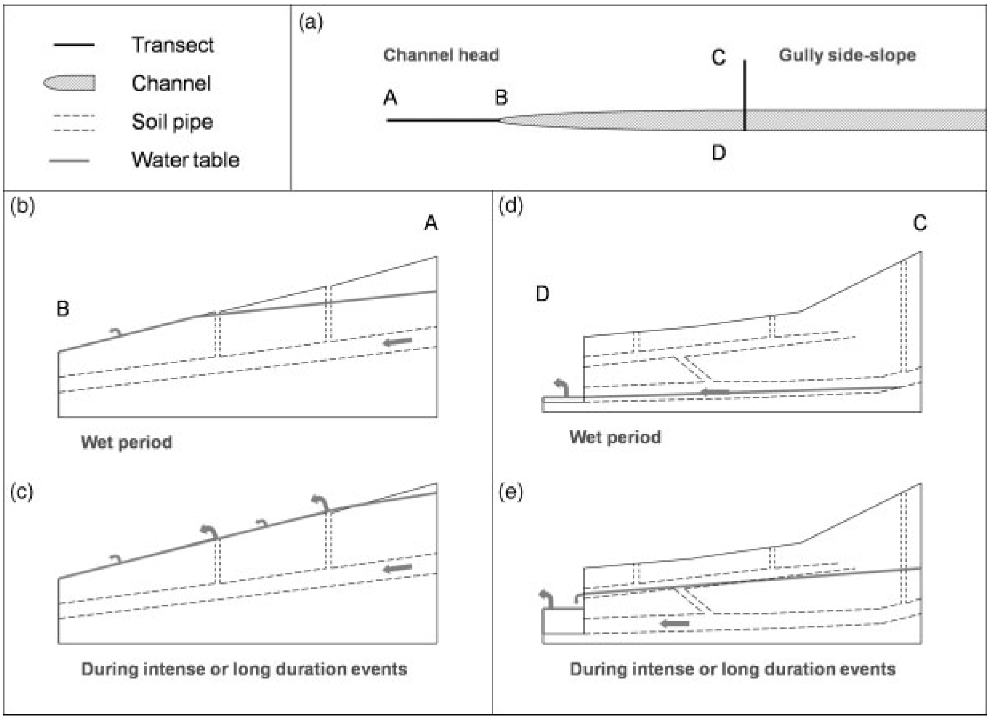

Figure 10. A perceptual model of the hydrological function (notably drainage) of soil pipes within humid tropical soils. The figure shows two different transects or vertical slices through the soil profile, one in a channel head depression (b and c), and one traversing a gully sidewall (d and e); both are located on an ephemeral stream channel (a). Two periods are illustrated for each transect. First, a 'wet period' is given to show hydrological functioning during a typical rain-event or within a few hours of such an event, where the ephemeral stream channel maintains some saturation and channel flow (b and d). The second period is for an episode of either intense rainfall or a long duration event where the soil profile within near-channel areas has a water-table at or close to the ground surface (c and e). The lower pipe in d and e is located close to the base of the B soil horizon

Possible role of cicada 'shafts' as outlets for lateral soil pipes

The widespread occurrence of vertical shafts excavated by cicada nymphs is observed in the Danum area. Overland flow running into these shafts has not been observed. As noted earlier, holes (which have the appearance of slightly enlarged cicada shafts) have, however, been observed to spout water during intense rainfall events and many have been shown to be connected to large, lateral pipes. Thus, some of these cicada shafts are considered to function as pipe outlets (Figure 2a) while others remain as dry shafts, though none have been observed to behave as insurgences within this particular humid tropical environment. This contrasts with some *regolith pipes* within Columbia, which have been shown to act as insurgencies for channel flow (Feininger, 1969). Given that cicadas are present throughout the humid tropics, the possibility that cicada 'shafts' can be modified by seepage forces from lateral pipes to act as pipe outlets needs to be examined throughout the region.

Recharge of lateral soil pipes

The mechanism for recharge of the lateral pipes remains unclear within the literature for piping within the humid tropics, and from wider observations at Danum. Given that the moisture content of the Danum subsoil remains close to saturation in so called *tension-saturated wedges* (Sherlock, 1997; Suhaimi, in prep) perhaps such zones within piped slopes rapidly saturate during rain-events and thereby recharge pipe flow (cf. Dunne, 1990). With rapid saturation, the network of small macropores within these wedges may fill connecting near-surface macropores with those in the lower soil profile (cf. Sidle *et al.*, 2001), which are themselves connected with the soil pipes.

A perceptual model of the hydrological function of soil pipes in the humid tropics

Based on the preceding review of literature pertaining to the humid tropics and the additional observations included, Figure 10 illustrates a tentative *perceptual model* (using terminology of Beven, 1991, 2001) of the hydrological functioning of soil pipes within humid tropical soils. This model is based particularly on direct observations of several pipe systems within the Danum area, East Malaysia (e.g. at 4°57·18′N, 117°48·12′E), but seeks to be consistent with published findings from elsewhere in the humid tropics where the necessary observations of pipe extent have yet to be made. Figure 10 shows two transects or vertical slices through the soil profile, one in a channel head depression (where there is a gradual slope rather than a gully headwall, as in Figures 5b, 10a–c), and one traversing a gully sidewall (Figure 10a, d, e). Two periods are illustrated for each transect. First, a 'wet period' is given to show hydrological functioning during a typical rain-event or within a few hours of such an event, where the ephemeral channel (Figure 10a) maintains some saturation and channel flow (Figure 10b, d). The second period illustrated is during either intense rainfall or a long-duration event where the soil profile within near-channel areas has a water-table at or close to the ground surface (Figure 10c, d; Bidin, 1995).

A large lateral pipe is shown running beneath the channel head (Figure 10b, c; following Baillie, 1975; Sayer, 2005). During typical rain-events, there may be no visible signs of these pipes (Figure 10b) except where the course of the lateral pipe intercepts the surface, collapses occur or a depression line is present (Burton, 1964; Baillie, 1975; Sayer, 2002, 2005; Figure 3). During intense or long-duration events, the water-table extends further up the depression so that it is above the ground surface at the locations of former cicada shafts connected to the lateral pipes (see Figure 2a). Under these conditions, the pipe flow then returns to the ground surface (to generate saturation overland flow) via the former cicada 'shafts' modified by pipe flow (Figure 10c).

In the sidewalls of incised gullies, those outlets of lateral pipes that are close to the channel floor (and close to the bedrock) are likely to maintain flow when the ephemeral stream channel has flow (Figure 10d). Such pipes are also likely to be only partially filled with water during these conditions. Furthermore, pipes higher within the profile may be dry (Figures 10d and 5a, b). When a large proportion of the riparian soil profile attains saturation during intense or long-duration events (Noguchi *et al.*, 1997; Sherlock, 1997; Chappell and Sherlock, 2005), then pipes higher within the profile may contain flow and also discharge into the ephemeral channel (Figure 10e; note that pipes higher within the profile of Figure 5a, b do show evidence of intermittent water-flow). Under these conditions, the deeper pipes may be completely filled with water and are under significant hydrostatic pressure.

This model illustrates some of the mechanisms of hillslope drainage by soil pipes. It needs to be extended to include the mechanisms that recharge the lateral pipes, though this needs more field survey and monitoring. Given the dearth of published work, this tentative model needs to be evaluated over a wide range of piped sites within the humid tropics.

CONCLUSIONS AND SUGGESTED RESEARCH PRIORITIES

The preceding review of the distribution and hydrological function of soil piping within the humid tropics was supplemented by additional information from the location stimulating the most published studies (Table I). The combined analysis has produced several findings, all needing to be explored with further research.

1. *Soil pipe distribution across the humid tropics* Most of the locations in the humid tropics with published reports of soil piping are within areas of Ultisol soil, though a few have either Alfisol or Andisol. Further work is needed to determine why Ultisol soils (rather than Oxisols or other locally dominant soils) have a greater reported incidence of piping. While there appears to be a link between the Ultisol soil order and soil piping, it is not clear how widespread the phenomenon is within this extensive soil type. A more extensive field survey of the incidence of soil piping throughout the humid tropics is needed, particularly within areas of Ultisol soil.
2. *Upslope and vertical extent* Several studies report the incidence and location of pipe resurgences (or outlets) within humid tropical basins. The most frequently active of these resurgences are in the lower sections of hillslopes (Burton, 1964; Banerjee, 1972; Löffler, 1974; Baillie, 1975; Walsh, 1980; Walsh and Howells, 1980; Bruijnzeel, 1983; Putty and Prasad, 2000; Sayer, 2002; Sayer *et al.*, 2006; Negishi *et al.*, 2007). Very few studies have, however, attempted to measure the upslope extent of soil pipes in the humid tropics. Those studies that have measured lengths within humid tropical soils have shown that they can extend up to 15 m (Löffler, 1974), 30 m (Sayer *et al.*, 2006; Figure 3b) or 90 m (Baillie, 1975) from pipe outlets. Within deep regolith strata in humid tropical Columbia, individual pipes have been shown to extend over several hundred metres (Feininger, 1969). Such limited data cannot be generalized, so it is imperative that pipe length is determined at many more humid tropical sites, most particularly at those sites where pipe studies have already taken place. The success of experiments at the Danum humid tropical site using diluted paint to establish possible connections between the resurgences of large, lateral pipes and upslope pipe collapses may be the first step in this local pipe mapping. This work would then need to be supported by excavation of pipe systems upslope from the pipe outlets, perhaps following a similar approach to that of Anderson *et al.* (2008). Injecting Plaster of Paris or expanding foam into lateral pipes via upslope shafts or collapses could help to maintain the integrity and visibility of the pipes during the excavation phase. Indeed, systematic surveys to show how many of the vertical shafts produced by cicada nymphs have become connected (by piping processes?) to the lateral pipe systems would be helpful in this regard. Known volumes of low viscosity resin could be poured into these shafts to identify those shafts not capable of being filled and hence connected with the lateral pipe network. Of the few cicada burrows examined by this method at Danum (East Malaysia), those that were isolated could be filled with the addition of 300–700 cm^3 of resin or dilute solutions of plaster.

Within humid tropical soils, lateral pipes are observed to be present at many different depths. Several studies do, however, report that those lateral pipes that are most often flowing occur at a depth of 1·3–1·5 m, which corresponds to the base of the soil, i.e. lower B soil horizon (Baillie, 1975; Walsh and Howells, 1988; Negishi *et al.*, 2007; this study). Several humid tropical studies have also reported the incidence of piping beneath the soil profile within deep regolith (Dixey, 1920; de Chételat, 1938; McBeath and Barron, 1954; Patz, 1965; Thomas, 1968; Feininger, 1969; Bremer, 1973). Within humid tropical countries, these deeper *regolith pipes* are often reported to form beneath a duricrust (Goudie, 1973). These studies have not involved hydrological investigations and are not in areas of the humid tropics with published hydrological studies on piping within the solum (i.e. A and B soil horizons). New studies that investigate the relationship between these deeper pipe systems (i.e. 2 to >10-m depth) and those that occur within 2 m of the ground surface (i.e. soil) are needed.

3. *Lumped response of pipe systems from monitoring pipe resurgences* Active pipe resurgences within humid tropical basins can be gauged relatively easily using weir boxes (e.g. Figure 2.3 in Sayer, 2005). These devices do not significantly affect the natural flow from pipes or surrounding soils, unlike devices installed within excavated hillslope pits (Knapp, 1970). As such, they provide a reliable way of measuring (preferential) hillslope drainage prior to the formation of channel flow (Negishi *et al.*, 2007) or overland flow outside of channels (Elsenbeer and Vertessy, 2000). The resulting high quality time series of hillslope drainage (e.g. Sayer, 2005; Negishi *et al.*, 2007) unaffected by artificial conditions imposed by the measurement make them amenable to characterization, physical interpretation, and are potentially useful for rainfall–runoff modelling.

Time constants (or residence times of response) of measured pipe resurgences in the humid tropics vary from those faster to those slower than the channel flow into which they drain. From the few time series available, the majority of the gauged pipes with outlets just above the height of the channel flow have responses dominated by a time constants longer in comparison to the channel flows. This would imply that pathways with recessions faster than those of deeper pipes contribute significant volumes of flow to the channels. Such faster paths within humid tropical basins may be related to a combination of (i) overland flow and pressure-wave effects in areas of saturated ground, (ii) hillslopes shorter than those with deep soil pipes or (iii) lateral pipes higher within the soil profile that have a more flashy flow regime.

As large, lateral pipes will offer less resistance to flow in comparison with the soil matrix (or small macropores) through which the pipes are recharged, quantification of the recharge processes may be more important than the pipe geometry in the interpretation of the time constants of response. These recharge processes are very poorly understood within humid tropical basins and warrant detailed investigation.

4. *Recharge of large, lateral pipe systems* Models of the recharge pathways of lateral pipes within temperate soils have been developed (e.g. Jones and Connelly, 2002). Field investigations within humid tropical basins are needed to allow similar quantification. In piped hillslopes where pipe resurgences are gauged (by existing or new structures), many automated measurements of soil moisture content and pressure potential are needed at multiple depths. With intensive spatial sampling these data would show which parts of the lateral pipe network are within saturated soil. One minute time steps may be needed given the flashy nature of some shallow lateral pipes (see Elsenbeer and Lack, 1996). Such data would also show the timing of the soil wetting (at different depths and slope positions) with respect of the time series of pipe outflow. These data could be analysed using a combination of transfer function approaches (cf. Fawcett *et al.*, 1997; Chappell *et al.*, 1999b), and physics-based models of soil moisture dynamics (Radulovich *et al.*, 1989; Germann *et al.*, 1997; Wollschläger *et al.*, 2009). These physics-based approaches would necessitate that hydraulic conductivity is sampled systematically throughout the monitored hillslopes. The saturated hydraulic conductivity (Ks) of typically fines-rich, Ultisol soils could be measured accurately with techniques such as ring permeametry or piezometer tests, as such methods are less sensitive to artificial smearing effects within fines-rich soils (Chappell and Lancaster, 2007). Ideally, the upper part of the unsaturated hydraulic conductivity curve would be measured with tension infiltrometry. These measurements may also show the presence of percolines and, where present, their relation to the lateral soil pipes. This destructive sampling would need to be undertaken after the soil moisture monitoring and perhaps at the same time as the excavation of the pipe networks discussed earlier.

Understanding the role of the small, but numerous macropores formed by tropical tree roots (van Noordwijk *et al.*, 1991) and soil fauna (Blanchart *et al.*, 1999) on these hydraulic conductivity measurements and the processes recharging lateral soil pipes is a fundamental research question (Beven and Germann, 1982) that has yet to be addressed within hillslopes of the humid tropics.

5. *Application* With detailed investigation of the spatial distribution of lateral pipes and surrounding hydraulic conductivity within specific hillslopes in the humid tropics, together with equally detailed monitoring of soil moisture dynamics, robust *conceptual models* (using the terminology of Beven, 1991, 2001) of piping within humid tropics may be capable of being developed. If a more extensive survey of the presence of piping within tropical Ultisols shows they are present within many hillslopes covered by Ultisols, then the availability of such models would allow better quantification of the hydrological processes over large areas of the humid tropics. This could allow improvement to rainfall–runoff models and hence a better understanding of why humid tropics basins may have very flashy responses. Secondly, this could allow improvement to models of ion transport that represent more accurately the migration of nutrients or contaminants within natural or disturbed hillslopes (Elsenbeer and Lack, 1996; Laabs *et al.*, 2002). Lastly, this would provide a better description of the flow

processes leading to gully development and sediment delivery within the humid tropics (Baillie, 1975; Sayer *et al*., 2006). These geomorphological processes would also benefit from studies quantifying the impact of forestry or agricultural disturbances to tropical pipe systems. As expected for a region containing a dearth of studies, this review has highlighted many aspects of soil piping that warrant further investigation.

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