Runoff Processes in Southeast Asia: Role of Soil, Regolith, and Rock Type

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1 *Abstract.* ■■

1. Introduction

Runoff processes determine the pathways that rainfall takes en route to a river. Within tropical regions, such as Southeast Asia (Fig. 1a), our knowledge of these water pathways is mostly derived from experiments conducted on individual hillslopes perhaps 10 to 300 m in length (Bonell 2004). This approach forms the discipline of hillslope hydrology (Kirkby 1978; Anderson and Burt 1990). Most of this research has been conducted within temperate environments, but some studies have been undertaken within the equatorial, seasonal, and dry tropics. This work has shown the presence of several types of runoff process within these globally important hydroclimatic regions. Some of the key phenomena and pathways identified are (i) a dominance of infiltration-cum-subsurface flow over overland flow in the generation of channel flow (Dubreuil 1985; Chappell et al. 1999a,b, 2004b; Bonell 2004; Chappell 2005a); (ii) the importance of lateral flow in organic near-surface layers (Bonell and Gilmour 1978; Bonell et al. 1981); (iii) the presence of "natural soil pipes" which route a proportion of water rapidly through hillslope soils (Baillie 1975; Jones 1990; Chappell et al. 1998; Chappell and Sherlock 2005); and (iv) the effects of soil compaction by vehicles or construction activities on the proportion of overland flow at local scales (Malmer and Grip 1990; Van der Plas and Bruijnzeel 1993; Ziegler et al. 2004).

2 Whilst it has been relatively easy to show that these pathways exist, it remains difficult to quantify the role of each pathway in the generation of riverflow within a specific headwater basin, let alone in areas where there are no experimental hillslope results nearby (Sherlock et al. 1995; McDonnell 2003; Chappell and Sherlock 2005). Indeed, the issue of how to generalise hillslope-scale observations to areas without

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direct observations of each runoff pathway is now at the forefront of scientific hydrology. Some scientists attempt to undertake this generalisation using maps of analogue information such as soil type (Nyabeze 2005), while others seek to abstract the resultant effects of different water pathways from hydrograph form (Kokkonen et al. 2003). As yet, neither method provides a perfect solution. Maps of soil type, for example, are classified primarily by a range of edaphic and pedological factors, not just factors controlling runoff processes (FAO-UNESCO 1990; Chappell and Ternan 1992; Soil Survey Staff 1999). Equally, different runoff pathways can give similar hydrograph forms, so that is not easy to identify which are the dominant runoff pathways purely from hydrograph analysis (Chappell 2005b). Despite these limitations, we believe that some information about runoff pathways is contained within maps of terrain characteristics, such as soil type or geology.

Even if our knowledge of runoff processes in tropical regions such as Southeast Asia is incomplete, we have still a duty to disseminate the existing data and theory, as it is these pathways that underpin many environmental processes. Clearly, runoff pathways control the time that water takes to reach rivers (Chappell et al. 2004b) and, thereby, whether the channel capacity is exceeded and flooding produced. They also affect the moisture status of soils in time and space and, thereby, the natural distribution of plants (Gibbons and Newbery 2003) and the agricultural productivity of soils (Baron et al. 1998). Further, they affect the migration of nutrients which affect soil edaphic status, plant distribution, and river water quality; this is particularly important where land-use change accelerates the loss of nutrients from soils to rivers (Chappell et al. 2004c). The movement of other solutes, such as agricultural pesticides and leaking industrial wastes, through soils and rocks towards rivers is similarly regulated by water pathways (Racke et al. 1997). Runoff pathways on the land surface, namely overland flow and channel flow, also regulate the amount of sediment mobilised and transported. Changes to these surface runoff pathways, therefore, affect the sediment load of tropical streams and rivers (Chappell et al. 2004b,c).

These environmental responses to spatial variations in runoff pathways have been shown to have major impacts in Southeast Asia (Bruijnzeel 1990; Chappell et al. 2004b,c). This region is particularly important for environmental research because of the rate of loss of the natural forest vegetation (Drigo 2004), the rapid industrial and urban development in the region, the rapid population growth, and the impact of this region on global climate (Chen and Houze 1997; Schneider 1998; Neale and Slingo 2003).

Given the overriding importance of runoff pathways and the Southeast Asia region, this study seeks to add to our knowledge of the controls on the spatial distribution of runoff pathways in this region of the equatorial and seasonal tropics. There are several key controls affecting the relative significance of each runoff pathway (Dunne et al. 1975). The controls include (i) rainfall characteristics (Smith 2004; Bidin and Chappell 2006), (ii) the magnitude of evapotranspiration relative to precipitation, (iii) surface and outcrop/rockhead topography (Kirkby 1975; O'Loughlin 1981; Zaslavski and Sinai 1981; Burt and Butcher 1985; Freer et al. 2002), (iv) the nature of the local soil and regolith and rock types, (v) the catchment depth/area relation (Blösch and Sivapalan 1997), (vi) the form and density of the channel network (Gregory 1976; Walsh 1996), and sometimes (vii) vegetation (Ziegler and Giambelluca 1998; Roberts

2000). Within this study, we focus on observations of the role of soil type, regolith type, and rock type on likely runoff pathways within Southeast Asia.

Ideally, we would restrict our observations on runoff pathways to tropical Southeast Asia. As there have been so few hillslope hydrology studies (i.e., studies with at least permeability and soil-water measurements) in Southeast Asia (Fig. 1a), we need to extend our analyses to include hillslope hydrology findings to the whole of the wet and seasonally wet tropics (Fig. 1b); although this still only gives a modest dataset of
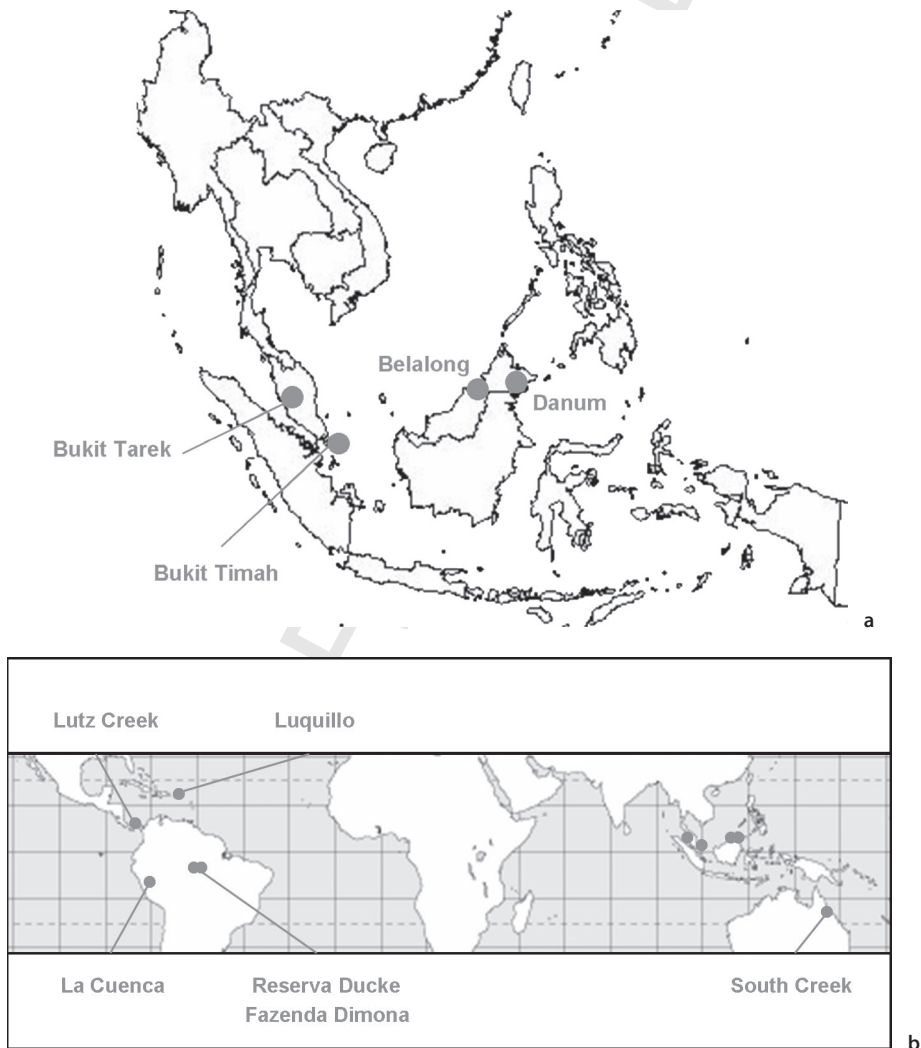

Fig. 1. Approximate location and distribution of published hillslope hydrology studies in Southeast Asia (**a**) and the whole of the humid tropics (**b**)

ten sites. These hillslope experiments have been conducted at South Creek, Australia (Bonell and Gilmour 1978; Bonell et al. 1981, 1983), Reserva Ducke, Brazil (Nortcliff and Thornes 1981), Fazenda Dimona, Brazil (Hodnett et al. 1997), Ulu Belalong, Brunei (Dykes and Thornes 2000), Bukit Tarek, Peninsular Malaysia (Noguchi et al. 1997), Danum, East Malaysia (Sinun et al.1992; Chappell et al. 1998, 1999a,b, 2004c; Chappell and Sherlock 2005), Luquillo, Puerto Rico (Schellekens 2000), Lutz Creek, Panama (Godsey et al. 2004; Kinner and Stallard 2004), La Cuenca, Peru (Elsenbeer and Lack 1996), and Bukit Timah, Singapore (Sherlock et al. 1995, 2000; Chappell and Sherlock 2005). Others have attempted to generalise the runoff pathways illustrated in these studies (Chappell and Ternan 1992; Elsenbeer 2001; Bonell 2004), particularly in the upper layers of the ground; we attempt to add to this work.

2. Effect of Soil Type

The strict definition of a soil as comprising only a topsoil (A horizon) and a subsoil (B horizon) is used here, where the underlying strata are defined as the parent material. Sometimes the parent material is rock, in other places it is a layer of unconsolidated geological materials or "regolith" overlying the rock. The regolith layer can be up to 50 m in depth in granitic terrains of Southeast Asia (Twidale 2004). In tropical regions, the unconsolidated material that forms the regolith can be in situ weathered rock or fluvial, alluvial, or colluvial sediments. Beneath the regolith (or directly beneath the soil) is the rock, which should be defined as it is not only a parent material for the soil, but is sometimes an important route for water—an issue which is often overlooked in tropical hillslope hydrology (Bonell 2004).

Soil type is classified using a range of edaphic and pedological characteristics (FAO-UNESCO 1990; Soil Survey Staff 1999). Hydrological characteristics affecting runoff pathways, notably permeability, porosity, and soil moisture status, are only one set of the many factors. Thus, a perfect correlation between hydrological characteristics and soil type should not be expected (Chappell and Ternan 1992). Note also that the classification of soil type is often incorrectly confused with the soil textural class, which is simply the mix of different particle sizes that make up each soil horizon.

2.1. Dominant Soil Type in Southeast Asia

Within the tropics, the dominant soil type is the Ferralsol group (USDA equivalent: Oxisol), and it covers 20% of the tropics, covering most of Amazon and Congo basins (Driessen and Dudal 2001). Ferralsol is, however, not very extensive in Southeast Asia or humid West Africa, where the dominant soil type is the "Acrisol-Alisol group" (USDA equivalent: Ultisol) (FAO-UNESCO 1976, 1990, 2004; Driessen and Deckers 2001; Fig. 2). In 1990, the Alisol group was newly defined and some Acrisol group soils, namely the more-unstable, base-poor soils, were reclassified as Alisol soils (FAO-UNESCO 1990). Strictly, Alisol soils can be distinguished from post-1990 Acrisol soils by the cation-exchange capacity being less than 24 cmol$^+$ kg^{-1} clay, as a result of the presence of unstable 2:1 clays (e.g., smectite). As a consequence, these soils have a poor soil structure in comparison to post-1990 Acrisol soils. The pre-1990
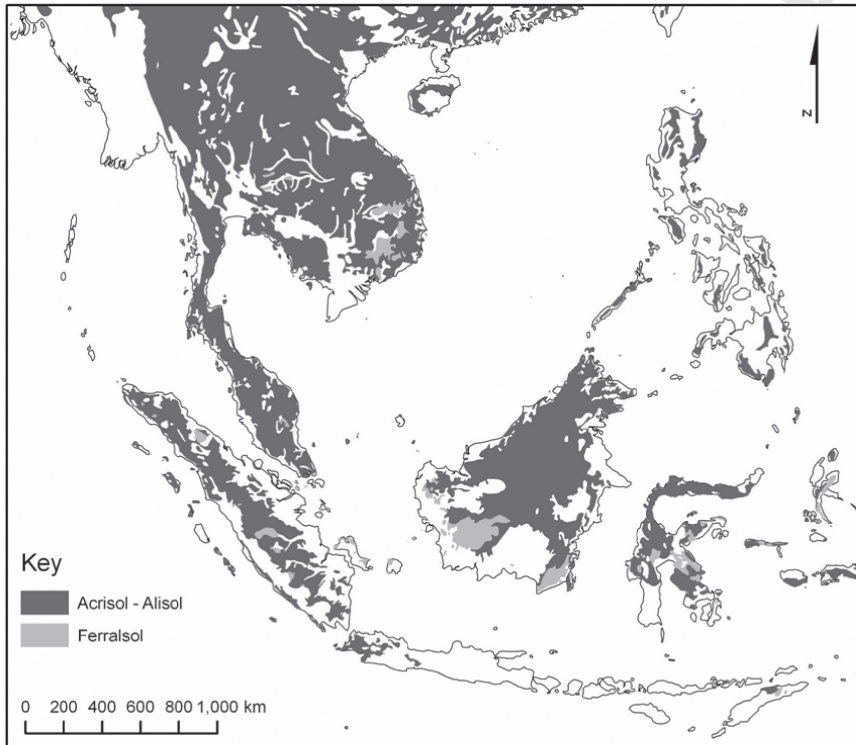
Fɪɢ. 2. Spatial extent of the Acrisol-Alisol (*dark grey*) and Ferralsol (*light grey*) soil groups in Southeast Asia (90°–130° E and 23.4° N to 12° S). [Adapted from FAO-UNESCO (2004) using ArcGIS version 9.1 (ESRI, Redlands, CA, USA)]

Acrisol soil group (Fig. 2) has, however, not yet been remapped into Alisol soils and post-1990 Acrisol soil. We, therefore, refer to the pre-1990 Acrisol soils mapped in Fig. 2 as the Acrisol-Alisol group.

2.2. Tropical Hillslope Hydrology Studies and Soil Type

Figure 1a,b shows the locations of the key hillslope hydrology studies (i.e., studies with at least permeability and soil-water measurements) published in the international literature. Six out of ten are on Acrisol-Alisol soils, the dominant soil of Southeast Asia (Sherlock et al. 1995; Noguchi et al. 1997; Chappell et al. 1998; Dykes and Thornes 2000; Schellekens 2000; Kinner and Stallard 2004). A further two studies (Bonell and Gilmour 1978; Elsenbeer and Lack 1996) have results from a mix of Acrisol-Alisol and other soils. There are only two studies on the dominant Ferralsol soil of the tropics, namely Nortcliff and Thornes (1981) and

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Hodnett et al. (1997), and only one that includes this soil with others (Bonell and Gilmour 1978).

Elsenbeer (2001) suggested that water pathways within tropical soils form a continuum from a Ferralsol end-member with predominantly vertical flow in the soil to an Acrisol end-member with predominantly lateral flow in the soil. This excellent start to a generalisation of water pathways using soil type does, however, have some significant inconsistencies. First, the water pathways for Danum (see Fig. 4 in Elsenbeer 2001) are placed by Elsenbeer (2001) in the intermediate category between the Acrisol and Ferralsol end-members. As the Danum experiments were conducted on Alisol soils (Chappell et al. 2001), the less well drained soils of the pre-1990 Acrisol class (Driessen and Decker 2001; Driessen and Dudal 2001), they should have a greater, not smaller, proportion of lateral flow than the post-1990 Acrisols. The observations of Chappell and Sherlock (2005) confirm this. Second, Elsenbeer (2001) classifies the Bukit Tarek soils as being part of the Ferralsol end-member, whereas they are Acrisol soils (Yusop 1996; Noguchi et al. 1997). Third, the soil at Bukit Timah is derived from a granite regolith very similar to that of Bukit Tarek. As the Acrisol soil at Bukit Timah has a significant proportion of vertical flow, although not total domination (Chappell and Sherlock 2005), we are more likely to expect a similar situation for Bukit Tarek. Last, the South Creek hillslope experiments were conducted on a range of soils including Ferralsols (Bonell et al. 1981, 1983) and, therefore, should not be all classified as in the Acrisol end-member class. We suggest that there may be a new model/generalisation that does not produce these major inconsistencies.

2.3. New Generalisation of Water Pathways in Tropical Acrisol-Alisol and Ferralsol Soils

We know that Alisol soils are distinguished from Acrisol soils on the basis of their clay mineralogy. Driessen and Deckers (2001) and Driessen and Dudal (1991) clearly showed that the internal drainage characteristics (notably permeability) of Ferralsol soils vary from very good to poor depending on clay mineralogy. Driessen and Dudal (1991, p. 161) state that Ferralsols with a clay mineralogy dominated by gibbsite are well drained, those dominated by 2:1 clays (e.g., smectite) have poor drainage, and kaolinite gives an intermediate state. Clay mineralogy affects soil permeability via its effects on the aggregate stability and structure of the soils (Driessen and Dudal 1991).

If we now consider the flow pathways at the sites that gave inconsistencies in the Elsenbeer (2001) model of soil type–flow pathways, we can see that the same soil type can have a wide range of proportions of vertical to lateral flow (Chappell and Sherlock 2005), and clay mineralogy may be the cause. The Alisol soil at Danum, with its high proportion of 2:1 clays (Chappell et al. 2001), gives a high proportion of lateral flow of approximately 60% of total percolation (Chappell and Sherlock 2005). In contrast, the Acrisol of Bukit Timah, with a dominance of kaolinite (Rahman 1992), has less than 10% lateral flow (Chappell and Sherlock 2005). Some of the highest rates of soil permeability published are for the Amazonian site of Nortcliff and Thornes (1981). Even given the uncertainties associated with permeability data (Chappell and Ternan 1997; Sherlock et al. 2000), such high permeabilities strongly

suggest no impediment to vertical drainage in the soil. A clay mineralogy dominated by gibbsite is indeed expected at this locality (Norcliff, personal communication). This observation contrasts with the Ferralsols associated with Acrisols in the South Creek catchment in tropical northeast Australia, where marked discontinuities in the soil permeability profile and significant volumes of lateral flow in the soil have been monitored (Bonell and Gilmour 1978; Bonell et al. 1981, 1983). Thus, at this site, the Ferralsols are expected to be dominated by kaolinitic or even 2:1 clays. By examining these key case studies, we would tentatively suggest a new model of the interactions between soil type, clay mineralogy, permeability, and flow direction (Fig. 3). Because of our suggested interaction between clay mineralogy and permeability, we call this model the ^{clay}K model (Fig. 3). Given the observations of flow direction at a range of sites, we can now tentatively add these locations to our perceptual model (Fig. 3). These placements are, however, preliminary and require further testing.
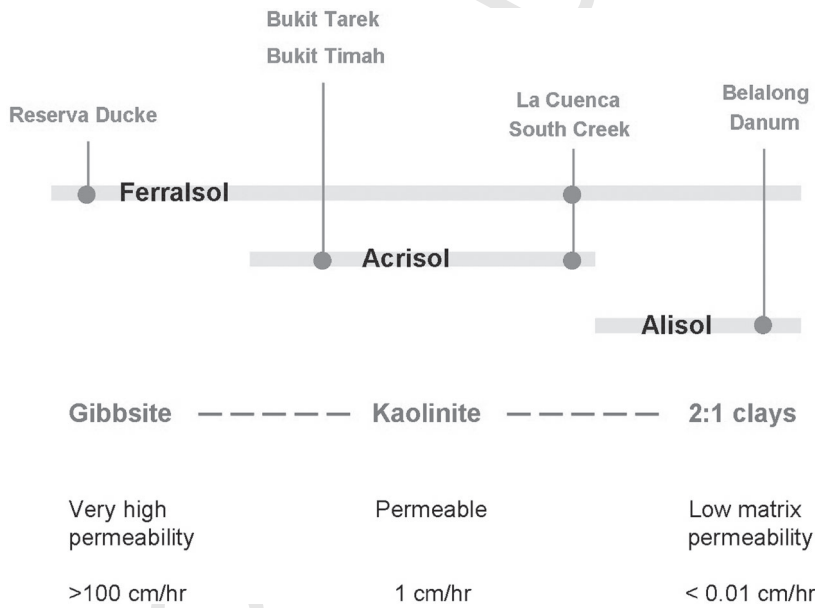

FIG. 3. The ^{clay}K model showing the range and end-members of subsoil permeability expected from the clay mineralogy of the three key soils of the humid tropics: Ferralsol, Acrisol, and Alisol soils. Locations with Ferralsol soils dominated by gibbsite have very high subsoil permeabilities, well in excess of 100 cm h^{-1} (e.g., Reserva Ducka, Brazil). Sites with Acrisol soils dominated by kaolinite clays have permeable subsoils (approximately 1 cm h^{-1}), e.g., Bukit Timah, Singapore, and Bukit Tarek, Peninsular Malaysia. Alisol soils are dominated by 2:1 clays (e.g., smectite) and have low matrix permeabilities (<0.01 cm h^{-1}) in their subsoil strata, as observed at Kuala Belalong, Brunei, and Danum, East Malaysia. The Ferralsol and Acrisol soils of La Cuenca, Peru, and South Creek, Australia, have subsoil permeabilities intermediate between the Bukit Timah and Danum sites, so are expected to have a clay mineralogy intermediate between kaolinite dominated and 2:1 clay dominated

Arguably, this model is slightly more robust than it needs to be, given that by far the most dominant soil present in Southeast Asia, as opposed to the whole of the tropics, is the Acrisol-Alisol group. Thus, it is the hydrological differences between these Acrisol and Alisol soils that are the most important. The inclusion of this other important soil does, however, allow wider comparisons with other flow pathway behaviour (e.g., Nortcliff and Thornes 1981). Given that the current map of Southeast Asian soils (FAO-UNESCO 1976, 2004) does not distinguish between Acrisol soils and Alisol soils, the observed hydrological differences between these two soils suggest that such a map is needed.

Most hillslope hydrological studies end the analysis of runoff pathways at this point, in that they only consider waterpath direction and magnitude within the soil (i.e., A and B horizons). At many locations, rainfall percolates much deeper than the soil before returning to form streamflow. Thus the analysis of runoff pathways at any location should consider whether a significant proportion of the rainfall is able to percolate into a deeper regolith or rock.

3. Effect of Regolith Type

In some landscapes, lithomorphic soils dominate, where only a topsoil (A horizon) directly overlying an impermeable rock is present, i.e., there are no subsoil or regolith layers. The steep mountain slopes of the Himalayas are a good example. Within Southeast Asia, lithomorphic soils such as Leptosols are rare (FAO-UNESCO 1976), with soils having a permeable subsoil and permeable deeper strata being common. Unfortunately, comprehensive maps of the extent, depth, and hydrological properties of regolith for the whole of Southeast Asia have not been produced. We do, however, know that weathering and mass movement of some rock types leads to a regolith that may be both deep and permeable. Tropical weathering of granitic rock in Southeast Asia and Australasia certainly leads to the development of a permeable regolith that can be 10–60 m in depth (Twidale 2005; Campbell 1997; Melinda et al. 2004). This regolith is normally described as saprolite. The granitic rock from which this saprolite is developed is shown in Fig. 4, for which we have abstracted the felsic and intermediate plutonic rocks from the Wakita et al. (2004) digital map of East and Southeast Asia. Granitic rocks with their deep permeable regoliths occur at many locations in Southeast Asia, and in some areas, notably Peninsular Malaysia (West Malaysia and Singapore), they are very extensive (Fig. 4). Furthermore, new hydrological analysis of watersheds on the Malay Peninsula would indicate that the presence of this regolith has a large impact on river hydrograph form (Chappell et al. 2004c; Chappell et al., in preparation) as a result of the deeper pathways within the regolith.

Quaternary materials are often unconsolidated. They have a very wide range of hydrological properties given that they can be produced by a wide range of geomorphological processes, including fluvial deposition, slope wash, mass movement, marine inundation, and glacial deposition. Where sediments are coarse (i.e., sands, gravels, and larger materials) and are not capped by impermeable soils (e.g., Gleysols), then percolation will move to depth within these regolith materials, before returning to generate riverflow. The impact on the hydrograph could be similar to that of the granite saprolite. Within Southeast Asia, Quaternary sediments are quite
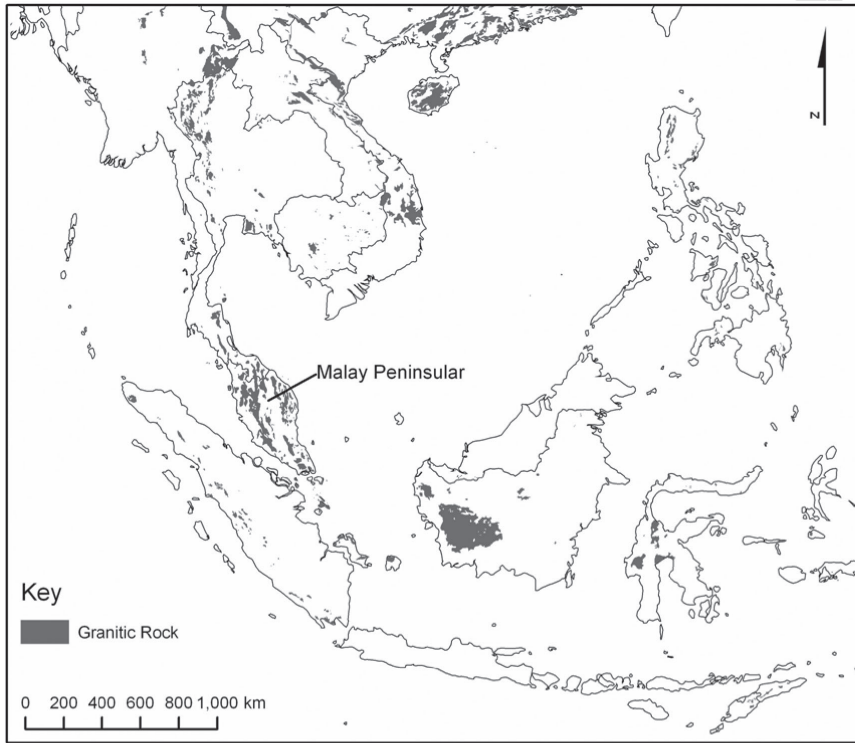
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Fɪɢ. 4. Spatial extent across Southeast Asia (90°–130° E and 23.4° N to 12° S) of the acid/intermediate plutonic rocks (notably granite) shown in *dark grey*. [Adapted from the digital data of Wakita et al. (2004) using ArcGIS version 9.1 (ESRI, Redlands, CA, USA)]

extensive (Fig. 5). Within the "Mekong Lowland" (Gupta 2005), which comprises much of Cambodia, and also in the Central Plain of Thailand extensive areas of sandy sediments have developed as a result of inundation by the Mekong and Chao Phraya rivers, respectively (Tien et al. 1988; Chiem 1993). In locations where these sediments are not capped by Gleysols (see FAO-UNESCO 1976, 2004) or marine muds (see Phienwej and Nutalaya 2005), and some relief is present to allow drainage, rainfall can percolate to depth within the sediments. There may be indications of this deeper flow within the damped hydrographs of the Stung Chinit experimental basin in Cambodia (see the hydrograph in Shimizu et al. 2005). Indeed, the sandy layers of the Quaternary sediments in Mekong Lowland, the Central Plain of Thailand, and other areas of Southeast Asia (see Fig. 5) are classified as an "aquifer" by Struckmeier and Richts (2004) and Phienwej and Nutalaya (2005), i.e., a substantial groundwater body having both a high permeability and porosity.

Where the depth of Quaternary sediments becomes substantial, perhaps several hundreds of metres (Shroder 1993; Najman 2006), the sediments become more consolidated and, with age, lithified to what might be described as rock, rather than regolith. The boundary between the regolith (or drift geology) and rock is often very indistinct in Quaternary materials.
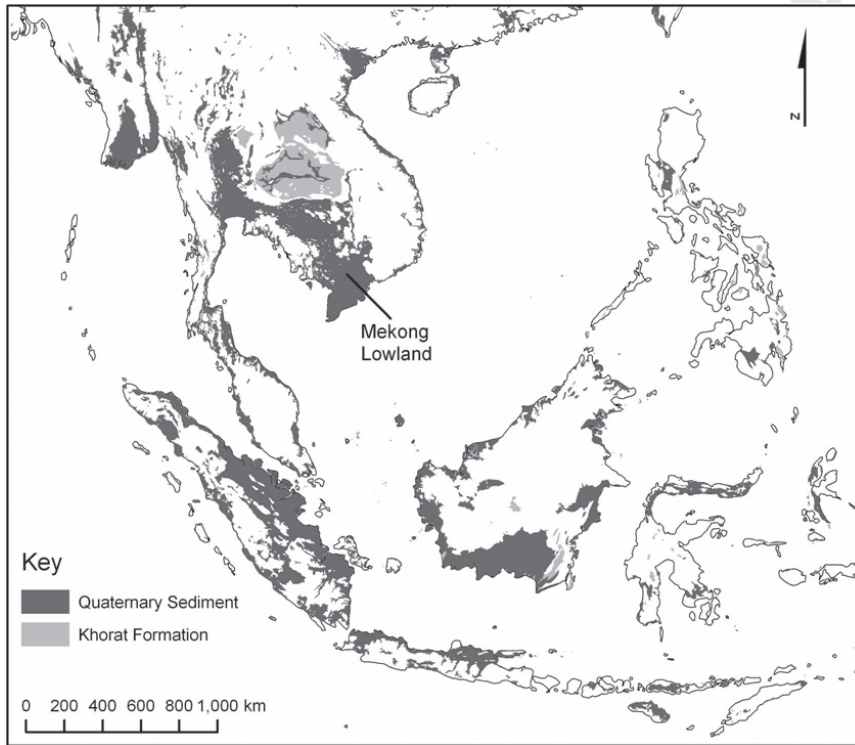
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Fɪɢ. 5. Spatial extent across Southeast Asia (90°–130° E and 23.4° N to 12° S) of the Quaternary sediments (*dark grey*) and the Khorat Formation (*light grey*) of Northeast Thailand. [Adapted from the digital data of Wakita et al. (2004) using ArcGIS version 9.1 (ESRI, Redlands, CA, USA)]

If a significant proportion of the areas mapped as granitic rock (see Fig. 4) and Quaternary sediment (see Fig. 5) do indeed have deep permeable regoliths, then rainfall will percolate to depth (i.e., 2–10 m or even 2–50 m) in many areas of Southeast Asia. Other geological formations found in Southeast Asia may also have permeable regoliths (Struckmeier and Richts 2004). The possibility of the presence of a deeper water pathway, therefore, needs to be considered at any study locality. Furthermore, there is a need to develop a map of the extent of deep permeable regoliths across the whole of Southeast Asia.

4. Effect of Rock Type

Whilst deep permeable regoliths seem to play an important role in the rainfall-runoff behaviour of some key areas in Southeast Asia, the extent of permeable rock seems to be much more limited. On a global basis, sandstone formations and carbonate rocks are the most extensive rocks with significant permeability and hence potential for deep-water pathways (Zektser and Everett 2004). The spatial extent of carbonate rocks in Southeast Asia is relatively limited (Gillieson 2005), as is the extent of
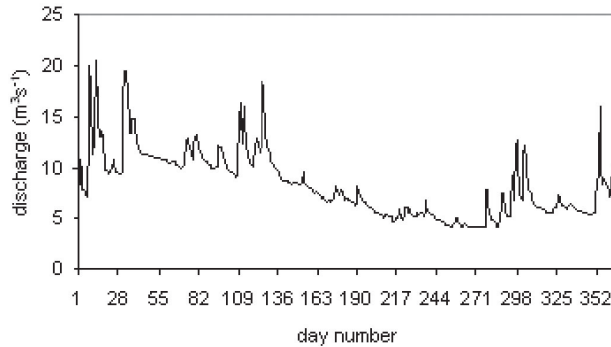
Fɪɢ. 6. Hydrograph of the 1033 km^2 watershed of River Kennet (United Kingdom) gauged at Theale during 2004. (Data supplied by the National River Flow Archive, UK)

onshore sedimentary basins dominated by sandstone. One locally important sandstone basin forms the Khorat Plateau of Northeastern Thailand (Heggemann et al. 1994; Racey et al. 1996). The geology is shown in Fig. 5. Although the solid geology may be an important deep groundwater resource (Struckmeier and Richts 2004; Zektser and Everett 2004), its rivers, part of the Mekong system, do not appear to be significantly damped (Douglas 2005; Mekong River Commission 2005), which would have indicated a deep pathway through the rock; this may be because relatively impermeable evaporite deposits cap the upper strata of the Khorat Formation (Carter and Bristow 2003). In other regions of the world, the movement of rainfall deep into permeable rock significantly damps the river hydrograph; see, for example, the long tails on the river hydrograph of the River Kennet in the United Kingdom, which is affected by the underlying Cretaceous chalk aquifer (Fig. 6).

For much of Southeast Asia, the solid geology is important not for the internal water pathways but as the parent material for the overlying regoliths and soils.

5. Generalisation, Limits, and Research Needs

We are acutely aware that the analysis we have presented so far is limited by the lack of availability of (i) hillslope hydrological studies available for particular combinations of soil, regolith, and rock and (ii) a map of the spatial extent of deep permeable regoliths (and their hydrological properties). Attempts at a generalisation of the relationship between water pathways and soil, regolith, and rock type within the humid tropics (Chappell and Ternan 1992; Elsenbeer 2001; Bonell 2004; Chappell and Sherlock 2005) are, however, valuable if only to highlight existing deficiencies and the need for ongoing and future research.

As a way of highlighting the possibility that deeper pathways exist within any tropical catchment under investigation, we propose that water pathway systems fall into four categories. The first, a "type I system," has a lithomorphic soil (A horizon) directly overlying an impermeable rock (an "aquifuge": Todd and Mays 2005). This situation is typical of the steep slopes of the Himalayas but also occurs over smaller areas of East Asia, e.g., in the Chinese headwaters of the Mekong River (FAO-UNESCO 1977).

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The runoff system that is likely to be much more extensive in Southeast Asia is the type II system. This situation is the same as a type I system, except that the soils are fully developed (e.g., Acrisol-Alisol, Ferralsol soils). Thus, water movement is expected in the subsoil as well as the topsoil, with percolation reaching a few metres into the ground. The flow pathways within the Baru and W8S5 catchments at Danum, Malaysian Borneo (Chappell et al. 1998; Chappell and Sherlock 2005) extend into subsoil horizons but cannot reach further, given that the solid geology is relatively impermeable and a regolith layer is lacking.

Of equal importance in Southeast Asia, given the extent of the mapped geology associated with regolith (see Figs. 4, 5), are type III systems. These systems have fully developed soils formed from deep permeable (or partially permeable) regolith overlying an impermeable solid geology. Good examples of type III hillslope hydrological study sites are Bukit Tarek (Noguchi et al. 1997) and Bukit Timah (Chappell and Sherlock 2005), which have Acrisol soils and a deep permeable granite saprolite.

The type IV water pathway system has fully developed soils and the presence of a regolith, but it also has permeable rock. Because of a lack of hillslope hydrological studies on rock aquifers in Southeast Asia, we are unable to cite a good example, but expect that such systems do exist at some localities (see Fig. 6). As this conceptualisation of the role of different strata to runoff pathways considers the presence/absence of four strata (i.e., topsoil, subsoil, regolith, and permeable rock) and results in four system types, we describe it as the Delta model, where delta is the fourth letter of the Greek alphabet. This conceptualisation or perceptual model (see Beven 2001 for the definition) is shown in Fig. 7.
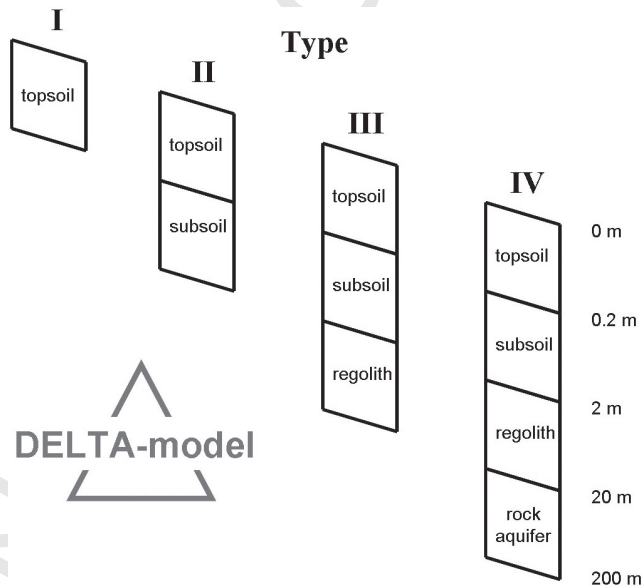

FIG. 7. Schematic representation of the Delta model, where water pathway systems are classified according to the presence of as many as four strata (topsoil, subsoil, regolith, and solid rock) with the names *type I* to *IV*. Example depths and the logarithmic depth scale are given
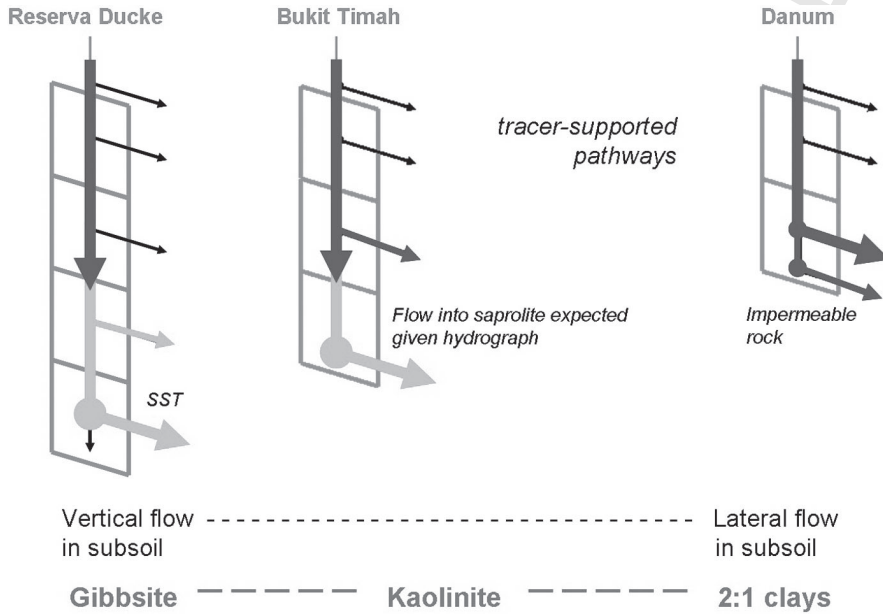
FIG. 8. The combined ^{clay}K model and Delta model showing the flow pathways for three key experimental sites across the humid tropics: Reserva Ducka (Nortcliff and Thornes 1981), Bukit Timah, and Danum (Chappell and Sherlock 2005). The *uppermost box* always represents the topsoil (see Fig. 7). The effect on the flow direction in the subsoil (i.e., vertical or lateral flow-dominated systems) together with the gradation from gibbsite to kaolinite to 2:1 clays is shown on the *x*-axis. The *dark grey arrows* show more certain flow pathways than the *light grey arrows*, and *arrow width* gives an estimate of the magnitude of the flow. Most certain pathways are derived from observations of tracer migration (Chappell and Sherlock 2005). There are no quantitative observations of the vertical flow into the underlying sandstone (SST) at Reserva Ducke or underlying granite saprolite at Bukit Timah, although significant qualitative evidence supports this hypothesis

To illustrate the utility of both the ^{clay}K and Delta model for comparing and gener-alising the results of runoff pathway studies, Fig. 8 shows the observed flow pathways within three experimental studies covering a range of situations found in the humid tropics.

We are presenting what we believe is a new perceptual model, which by definition is a simplification of reality (Beven 2001); this means that there will be omissions, uncertainties, and possibly errors with this approach. First, even if the ^{clay}K concept were to hold, soil permeability varies considerably within the same soil horizon of the same soil type at any one locality (Nielsen et al. 1973; Bonell et al. 1983; Chappell and Ternan 1992; Chappell and Sherlock 2005). Any one hillslope may exhibit a very different local permeability pattern and, thereby, flow pattern from a "typical" or representative site.

Second, soils are classified according to a range of physicochemical characteristics, not just hydrological characteristics. As a consequence, we should not expect there to be a perfect correlation between soil type and permeability or pathway direction (Chappell and Ternan 1992).

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Third, small-scale soil maps such as the FAO-UNESCO (2004) digital map are gross simplifications of the way in which soil types change over several kilometres, let alone over a few hundred metres. Key changes in soil types along a soil catena, the sequence of associated soils found along hillslope transects (Milne 1935), impact on the resultant behaviour of the whole hillslope but are not shown on small-scale maps (Chappell and Ternan 1992).

Fourth, tropical hillslope studies have shown the importance of phenomena such as percolines and natural soil pipes to runoff behaviour at hillslope scale (Bunting 1961; Baillie 1975; Jones 1990; Chappell et al. 1998, 2001). We know that such features are present within many tropical soils and certainly within the Acrisol-Alisol soils that dominate in Southeast Asia (Chappell and Sherlock 2005; Chappell et al. 2006). There is, however, insufficient research to be able to predict the hydrological impact of these phenomena for a particular soil type or locality.

Fifth, even where maps of regolith can be derived, considerable spatial variability in the depth and hydrological properties of the materials is expected, given their diverse formation processes.

Sixth, factors other than soil, regolith, and rock types affect runoff pathways but are not explicitly considered, e.g., the degree and dynamics of saturation within the subsurface. For example, where an extensive regolith is permanently saturated in an area of very low relief, as may be the case in parts of the lower Mekong, such strata may not play a part in the rainfall-runoff pathways. Other factors that would be expected to impact on runoff pathways in Southeast Asia include the rainfall characteristics (Robinson and Sivapalan 1997), surface topography, outcrop/rockhead topography (i.e., shape of the upper surface of the impermeable rock), and vegetation.

Seventh, the vertical to lateral flow ratio and the residence time of the water within a catchment system changes with scale. For example, as catchment scale increases from a few hectares to thousands of kilometres square, then there is a tendency for residence time to increase as the depth:area relationship reduces.

Last, the different techniques used to estimate the direction and magnitude of water pathways within individual experimental hillslopes can give very different results (Sherlock et al. 2000; McDonnell 2003; Chappell and Sherlock 2005). So, the findings that we are trying to correlate with soil, regolith, or rock type may themselves not be an accurate representation of the flow pathways.

All these issues need to be considered in improving our conceptualisation of runoff processes within Southeast Asia, which explains why we have yet to release our preliminary version of a conceptual model (i.e., a numerical version of a perceptual model: Beven 2001) for testing by others. Following further development, including comparisons with physics-based model simulations at the hillslope-scale (cf. Chappell and Binley, 1992), we will make the conceptual model available for testing with the tropical hillslope data of other investigators.

6. Implications for Runoff Processes in the Mekong Basin

The Mekong drainage basin is the largest in Southeast Asia at 795 000 km^2. It is also strategically important given that its riverflow is sourced from six nations (Cambodia, China, Lao PDR, Myanmar, Thailand, and Vietnam). There are, however, very few

studies detailing the runoff processes within this basin. We are able to make some comments on the likely runoff processes within the Mekong Basin, given (i) the proceeding analysis of hillslope studies from around the humid tropics, (ii) the interpretation of available Geographic Information System (GIS) data for soils and rocks (see Figs. 2, 4, 5), and (iii) the tentative perceptual models of the relationship between flow pathways and the soil, regolith, and rock type (see Figs. 3, 7, 8). Such comments are certainly no replacement for the field experimental studies that are needed within the basin.

The dominant soil type in the Mekong basin, as in Southeast Asia as a whole, is the Acrisol-Alisol group (FAO-UNESCO 1976, 1977, 2004). If the proceeding analysis of Alisols being dominated by lateral flow and Acrisols having mostly vertical flow is accurate, this will have an impact in the Mekong. Existing soil data, notably cation-exchange capacity (CEC) and clay content, should be reexamined or new data collected that allow (i) specific research hillslopes or watersheds to be classified as either Alisol or (post-1990) Acrisol, and (ii) the derivation of a Mekong soil map that distinguishes these two soil groups.

Cambodia and hence to the lower reaches of the Mekong basin are largely underlain by Quaternary sediments, some of which are coarse fluviatile deposits (Tien et al. 1988; Chiem 1993). In these areas, a dominance of Acrisol over Alisol soils would mean that rainfall would be expected to percolate through soils into and through these sediments before reaching rivers. If this is the case, the study of the hydrological characteristics and response of regolith at a depth of several metres is important to any catchment hydrological research in this region.

Within this same downstream sector of the Mekong basin, the presence of Gleysol (USDA Aquic suborders) and Fluvisol (USDA Fluvent) over the Mekong delta and along most of the Cambodian sections of the main channel of the River Mekong and Tonle Sap tributary (FAO-UNESCO 1976, 2004) is equally significant for hydrological study and interpretation. Gleysols and most Fluvisols are slowly permeable (Driessen and Deckers 2001; Driessen and Dudal 1991); this means that within the Mekong floodplain areas (approximately 10 km on either side of the main channels) either (i) the underlying regolith parent material is also locally slowly permeable or (ii) the soil would restrict vertical percolation to the regolith strata. Either situation would mean that rapid routing of rainfall to the main river via the topsoil (or even surface) pathways would be expected within these floodplain areas. These areas would effectively behave like a type I flow pathway regimen. Direct field monitoring is required to confirm the role of this pathway along the lower Mekong floodplain.

The other region of the Mekong basin containing Gleysols along main channels, and indeed Gleyic Acrisols/Gleyic Alisols across most of the area, is the Khorat Plateau (FAO-UNESCO 1976; see Fig. 6). The presence of these less-permeable soils may be the result of the less-permeable evaporite upper strata of underlying rock that form the parent material (Carter and Bristow 2003). This observation would also support the idea that the Mae Nam Mun River system is hydrologically isolated from the deep aquifer beneath the Khorat Plateau. Further study is needed to identify the possibility of connections of this deep aquifer with the surface drainage.

In the northern headwater of the Mekong, north of the Tropic of Capricorn, the downstream reaches have Fluvisol soils, while the extreme headwaters and steep valley slopes have poorly developed, lithomorphic soils in complexes of Lithosols,

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Xerosols, Kastanozems, and Rankers (FAO-UNESCO 1997, 2004). A very shallow or type I flow pathway system would be expected in these lithomorphic soils.

Given that the Ferralsol is the dominant soil of the tropics, it is worth noting the extent of this soil in the Mekong basin. Very few areas of the Mekong are mapped as being dominated by Ferralsol soils. The only areas are in the extreme southeast of the basin where parts of the Tonle Srepok and Dak Dear basins (Vietnam) have Ferralsol soils (FAO-UNESCO 1976, 2004; see Fig. 2) developed on basaltic rocks (Wakita et al. 2004).

In summary, understanding the spatial patterns of runoff processes within the Mekong requires further work to isolate the regions of Alisol soil from Acrisol soil, particularly where the presence of Acrisol soil would allow much percolation of rainfall to depth within the extensive regoliths of the Mekong lowlands. Further study of the effect of Gleysols and Fluvisols, particularly in the same Mekong lowlands, is similarly important, in this case to identify the presence and role of near-surface and hence rapid rainfall-runoff pathways.

7. Conclusions

This analysis has examined the role of soil, regolith, and rock type on runoff pathways within tropical Southeast Asia. Direct observations of runoff pathways should always be a key element of such analyses, but there are insufficient published hillslope hydrology studies for the Southeast Asian region to make robust generalisations. As a result, we have attempted generalisations of water pathway to soil–regolith–rock linkages for studies undertaken throughout the whole humid tropics (i.e., wet tropics and seasonally wet tropics). We then examined the spatial patterns of soil–regolith–rock information for the whole Southeast Asia region available from the latest sources (FAO-UNESCO 2004; Wakita et al. 2004) to assess the importance of each strata and the potential interactions between the strata. Throughout, we have acknowledged the considerable uncertainties within (i) the data sources (GIS data and experimental results) and (ii) our generalisations. Implicit within this is also our focus on only one factor affecting runoff pathways, namely the soil–regolith–rock system; we acknowledge the additional role of factors such as the rainfall regimen, topography, and channel network. It is, however, our view that generalisations from a wider range of observations and conditions from the whole humid tropics might give insight into phenomena within Southeast Asia or indeed its largest watershed, the Mekong, where sufficient local observations are absent.

It is hoped that we have demonstrated that previous generalisations (or perceptual models) of flow pathways in the humid tropics have significant inconsistencies. A new model (^{clay}K) is proposed which addresses the inconsistencies in the soil component by utilising clay mineralogy. Where permeable regoliths or rocks are present, and we show where these may be present, rainfall may percolate to a considerable depth before returning to form riverflow. Very often hillslope hydrological studies and larger-scale hydrological modelling exercises have ignored these deeper pathways (Bonell 2004; Chappell et al. 2005). Thus, there is a second reason for understanding the role of surficial geology (i.e., regolith) and solid geology in rainfall-runoff research. To highlight the role of these deeper strata, we propose a new model called the Delta

model. For the moment, this remains a perceptual model (i.e., a qualitative descrip-
tion of ideas: Beven 2004). With more data and analysis, we hope that this could
become a conceptual model (i.e., a quantitative description of key ideas: Beven 2004).
Our aim is to encourage new quantitative field research into the role and interaction
of soil, regolith, and rock strata on runoff pathways.

The analysis of the data sources (GIS data and experimental results) has highlighted
the potential importance of Acrisol-Alisol soil groups and regolith associated with
granitic rock and Quaternary sediments within Southeast Asia. These are important
considerations for hydrological research within the Mekong basin, but this subregion
also has relatively extensive regions of slowly permeable soils overlying the Quater-
nary sediments (i.e., the regolith underlying Cambodia) and a deep aquifer system
within the solid geology of the Khorat Plateau. The nature of the interaction between
deeper hydrological systems and the surface hydrology where there are impeding
layers (perhaps considered as "aquitards": Todd and Mays 2005) must be clarified.

Our main point is that field observations are needed to support the ideas forwarded
and that this research needs to take a holistic approach to the hydrology of soils,
regoliths, and rock.

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