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Return-flow prediction and buffer designation in two rainforest headwaters

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Abstract

Within tropical rainforests, most rainfall infiltrates the soil to then return to the surface within stream channels or from streamside soils. The wet zones created are very sensitive to disturbance and should be protected from forestry (or agricultural) operations. This study identifies the location of returning subsurface waters using measurements of the topsoil moisture content and first-order, stream-head location. The ability of a topographically based index to predict the location of both channel heads and wet soils is then evaluated to assess its utility for streamflow generation modelling and the designation of buffer or protection zones.

Analysis of the location of perennial stream-heads in the 0.44 km^2 Baru catchment (East Malaysia) indicated that these could be predicted by the Kirkby topographic index (λ spatial distribution) to within two terrain pixels (each 20 m $\times$ 20 m). Within this catchment, topography, therefore, played a key role in the generation of perennial streams, and the λ spatial distribution may be useful in locating the perennial stream network on digital maps for objective 'hydrological buffer zoning'. The spatial structure of 468 soil moisture content measurements within the 0.21 km^2 Huai Pacha catchment (Northern Thailand), was identified by variogram analysis and then used to interpolate the data. A patchy distribution of near-saturated soils was observed along the perennial streams. The λ spatial distribution was poorly correlated with the whole moisture data-set, showing the need to characterise soil and geological variability at this locality in addition to topographic factors. The wet patches did, however, coincide with areas of high topographic convergence and with values of the λ spatial distribution greater than 9 ln(m). Use of this threshold in the λ spatial distribution, rather than a fixed-width riparian buffer defined smaller protection zones with a higher proportion of the sensitive saturated or near-saturated soils. Consequently, the λ-based buffers would be more efficient, easier to justify scientifically, and allow access to more of the timber growing on less sensitive, drier soils. More studies on return-flow are needed in tropical rainforests to add to our understanding of runoff processes, validate distributed hydrological models and provide a hydrological basis for the objective definition of forestry buffer or protection zones within this critical environment.

Keywords: Channel head; Kirkby topographic index; Riparian buffer zone; Soil moisture; TOPMODEL

1. Introduction

1.1. Need for return-flow studies in tropical rainforests

In most humid forests, streams are generated primarily by subsurface waters returning to the surface at the streambed or in streamside soils, which then generate saturation overland flow (Ward, 1984). These exfiltration processes are called 'return-flow' (Cook, 1946). We need a sound understanding of these phenomena within tropical rainforests to address four key issues.

First, the magnitude, location and extent of return-flow governs the streamflow or storm hydrograph (Dunne et al., 1975; Kirkby, 1975; Woods and Sivapalan, 1997) and thus the nature of river floods.

Second, it is important to understand where return-flow is located, as this information aids in the development and parameterisation of physically based, rainfall-runoff models, e.g., TOPMODEL (Beven and Kirkby, 1979), TOPOG (O'Loughlin, 1986, 1990; Vertessy and Elsenbeer, 1999), SHE (Redsgaard et al., 1992). This becomes critical as such models are increasingly used in forestry and agro-forestry management (Wollock et al., 1990; Bonell and Balek, 1993; Costantini et al., 1993; Prosser and Abernethy, 1999; Silberstein et al., 1999; Bonell and Molicova, 2003).

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Thirdly, we know that tropical forestry has some impact on river behaviour, erosion and nutrient losses (Chappell et al., 2004c), yet there is a fundamental lack of experimental studies examining water, sediment and nutrient flow-pathways within managed or undisturbed tropical rainforests (Tangtham, 1994; Bonell, 2004; Chappell et al., 2004c). This means that generalisations of, for example, the amount of water-flow close to the ground surface in natural forest slopes, or the amount of water-flow on forestry skid trails in tropical rainforests are highly uncertain (Chappell and Sherlock, 2005; Chappell et al., 2006). This uncertainty makes it difficult to evaluate the hydrological basis of particular best management practices or guidelines (Thang and Chappell, 2004; Chappell, 2005). The most important location to study these pathways is within areas likely to generate return-flow.

Fourthly, within tropical rainforests managed for timber production, knowledge of the location of these saturated areas aids our ability to predict local sensitivity to soil disturbance and hence areas to focus protective measures. The location and extent of zones of saturated soil close to streams affect whether: (a) whether eroded sediments from upslope areas reach or settle prior to the stream, (b) the sensitivity of stream-side soils to mechanical damage and disturbance by forestry vehicles, and (c) the likelihood that nutrients released by harvesting activities can reach streams. Thus a map of perennial channels and associated wet stream-side soils should be one of the minimum criteria governing the location of 'buffer zones' that are now part of sustainable forestry management systems (Cassells and Bruinjzeel, 2004; Thang and Chappell, 2004). Partly because of the limited availability of experimental data on flow-pathways within tropical rainforests (Bonell, 2004), and the lack of research on methods to hydrologically define buffer zones (Bren, 1998), there is much uncertainty and debate about how such 'hydrological buffer zones' should be defined and mapped in tropical rainforests (Bren, 2000; McGlynn and Seibert, 2003; Bruijnzeel et al., 2004; Thang and Chappell, 2004).

1.2. Topographic prediction of return-flow

As the observation of flow-pathways requires very local measurements on small sections of hillslopes (so-called 'hillslope hydrology'), most studies on these flow-pathways have focused on micro-catchments in stream headwaters, which are between 0.1 and 10 km^2 in area (Bonell, 2004). Our research in such micro-catchments within the South East Asian tropical forests (i.e., Baru and W8S5 in East Malaysia, Bukit Timah in Singapore, Mata Ikan in Brunei, Huai Pacha, Huai Daf and Kog Ma in Thailand) supports the idea that most rainfall infiltrates the soil, flows towards the stream channels (in rock fractures and soil) to re-emerge in the channel bed or banks or from the soils adjacent to the stream (e.g., Sherlock et al., 1995; Sherlock, 1997; Chappell et al., 1998, 1999a,b, 2004a,b; Franks et al., 1997; Vongtanaboon, 2004; Chappell and Sherlock, 2005). Despite these extensive visual observations, until this study we have not systematically measured soil moisture content across these micro-catchments (only in local plots or transects); yet we have used models which make assumptions about the nature of soil moisture patterns across them (e.g., Franks et al., 1997; Chappell et al., 1998, 2004a). These studies have used the hydrological model called 'TOPMODEL' (Beven and Kirkby, 1979).

Most studies using TOPMODEL assume that soil moisture content, strictly moisture storage in the active subsurface profile, is linearly related to a topographic index, λ spatial distribution. The value of λ (ln(m)) at any point in the catchment is a directly related to the upslope contributory area (m^2) to that point (a) and indirectly related to the tangent of the surface slope angle (β), in log space, i.e.:

$$\lambda = \ln\left(\frac{a}{\tan\beta}\right)$$

(Kirkby, 1975; Beven and Kirkby, 1979). Indeed, such studies typically assume that patterns in soil or geological properties are insignificant when compared with the effect of topography (Beven and Kirkby, 1979). In order to simulate the streamflow behaviour and the dynamics of soil moisture within a catchment, therefore, requires only past rainfall and streamflow data and a detailed topographic map. With such limited requirements for input data, the model can constrain much more of the predictive uncertainty in comparison with more complicated, fully distributed physics-based models (Beven, 2001). Further, the model is also attractive for use within tropical rainforest environments, as it normally does not require the collection of soil and other terrain characteristics (e.g., soil permeability, total and macro-porosity, surface roughness). Other models, e.g., TOPOG, use similar topographic indices and can have structures that similarly do not demand large numbers of soil/rock characteristics (O'Loughlin, 1990; Vertessy and Elsenbeer, 1999; Brasington et al., 1998). One of the main questions over the use of these topography-based hydrological models has been the accuracy with which a topographic index (which excludes soil/rock variability) can estimate true patterns of: (a) surface saturation (O'Loughlin, 1981; Barling et al., 1994; Merot et al., 1995), (b) soil moisture content (Chappell and Franks, 1996; Sulebak et al., 2000; Crave and Gascuel-Odoux, 1997; Western et al., 2004), (c) soil water potential (Burt and Butcher, 1985; Molicova et al., 1997), or (d) water-table depth (Troch et al., 1993; Jordon, 1994; Moore and Thompson, 1996).

For this evaluation study, we have measured the spatial pattern of moisture content in the topsoil across one of our catchments. When saturation is seen within the topsoil, often as a result of water from upslope areas converging on these areas, then the soil-water may emerge from the ground and combine with precipitation falling onto these saturated soils, and generate 'saturation overland flow'. If generated on soils close to streams, this surface flow will rapidly reach the streams (Dunne et al., 1975) and carry with it any mobile sediments or chemicals.

After a geostatistically based interpolation of our distributed soil moisture data, the resultant map has allowed us to evaluate the common assumption—that patterns in the topographic index, λ, match those in the topsoil moisture observations, with systematic variations in soil and geology playing no role.

TOPMODEL, which has this assumption, has already been applied to tropical catchments in French Guyana (Molicova et al., 1997), Ivory Coast (Quinn et al., 1991), Malaysia (Franks et al., 1997; Chappell et al., 1998, 2004a; Ismail, 2003; Kavetski et al., 2003), Panama (Kinner and Stallard, 2004), Southern China (Chen et al., 2003), Tanzania (Campling et al., 2002a) and Thailand (Tantasirin, 2002; Kwanyuen and Pooworakulchai, 2003; Vongtanaboon, 2004). Others have assumed that the 'wetness index' of O'Loughlin (1990: see Campling et al., 2002b for comparisons) similarly matches soil moisture patterns and have applied the TOPOG model in other tropical regions of Australia (Costantini et al., 1993), Peru (Vertessy and Elsenbeer, 1999) and Puerto Rico (Schellekens, 2000). Critically, only Molicova et al. (1997) have, however, presented any comparisons between the patterns in soil-water variables and the topographic index within tropical catchments. Many studies conducted in temperate regions have shown mismatches between the topographic index and soil moisture or capillary potential patterns (e.g., Burt and Butcher, 1985; Crave and Gascuel-Odoux, 1997). Our study may show similar findings, but for tropical soils. This would not be a disappointing result. Indeed such a result, if it occurs, may indicate that other phenomena (e.g., percolines, soil catenas, fractures, soil pipes) may be as significant in controlling water-flow as topography, thereby adding to our understanding of flow-pathways within tropical soils.

Subsurface water emerging from soil near to streams is most apparent during rain-storm periods, and within some catchments the extent of soil saturation and the areas with return-flow are very dynamic (see e.g., Western et al., 1998). Subsurface water generating 'perennial streams', by definition, does so continuously. Above the head of these perennial channels, flow may emerge for part of the year (due to seasonality in the rainfall), or only for a short period immediately after a rain-storm (Hewlett and Nutter, 1970). These channel reaches upstream of the perennial channels are called 'intermittent channels' and 'ephemeral channels', respectively (Dingman, 1994), and are clearly an extension of the channel system (Hewlett and Nutter, 1970). A further way of evaluating the reliability of the topographic index in predicting return-flow would be to monitor the presence of flow at all locations within a channel network for 1 year and thereby: (a) identify the heads of perennial channels, and (b) to see if these locations have similar topographic index values. Examining whether consistent topographic index values are produced for every perennial channel head in a micro-catchment is clearly useful in return-flow or hydrological buffer zone identification studies, but perhaps a slightly less stringent test than the prediction of complex patterns of topsoil moisture across the whole micro-catchment.

1.3. Aim and objectives

Given the need and hence aim for a greater understanding for return-flow patterns and processes within tropical rainforests to improve: basic science (Bonell, 2004), and methods of defining hydrological protection zones (Bren, 2000), three objectives are addressed:

(1) Determine if the heads of perennial channels within a tropical rainforest micro-catchment are located at consistent topographic locations.
(2) Determine if the pattern of moisture content within the topsoil of a tropical rainforest micro-catchment during the wet season, and is matched by the pattern in the Kirkby topographic index.
(3) Determine the implications of these new findings on the location of return-flow within two tropical rainforest micro-catchments for defining of hydrological buffer zones.

The first objective utilised sampling and analysis within the Baru experimental catchment in Sabah, Malaysian Borneo. The Huai Pacha experimental catchment in Northern Thailand was used to study the second aim. Results from both catchments were then used to consider the forestry implications to be addressed by the third aim. Woods and Sivapalan (1997) have called for more studies addressing streamflow generation mechanisms that combine topographic analysis of channels and wet slope soils. This is particularly important in tropics where there has been little internal-state validation of topographic models (Molicova et al., 1997; Chappell et al., 1998, 2004a; Vertessy and Elsenbeer, 1999). Further, Bonell and Balek (1993), Bonell and Molicova (2003) and Thang and Chappell (2004) have called for greater use of such understanding in tropical forest management.

2. Research sites

2.1. Micro-catchment selection and key features

The greatest rate of physical disturbance of tropical rainforest environments is currently occurring in South East Asia (Drigo, 2004). There is, therefore, some urgency that forestry management practices (notably, ground skidding and hydrological buffer designation) in this region need to be optimised with the aid of scientific studies. The two micro-catchments we have selected for study of return-flow both comprise of the Ultisol soil order (Chappell et al., 1999b; Vongtanaboon, 2004), which dominates in the South East Asian region (Lal, 1995). One micro-catchment, the 0.44 km^2 Baru experimental catchment lies only 5° north of the equator and consequently has an aseasonal rainfall regime (Chappell et al., 2001) and wet evergreen rainforest (Whitmore, 1988). In some contrast, the 0.21 km^2 Huai Pacha experimental catchment lies at 18° north of the equator, receives rainfall only in the Summer (Dairaku et al., 2000; Boochabun et al., 2004) and consequently has dry evergreen rainforest (Whitmore, 1988). While both catchments are covered by disturbed rainforest, the Baru was disturbed by commercial, selective logging, the Huai Pacha was disturbed most recently by shifting cultivation. Other details specific to each experimental catchment are now presented.

2.2. Baru experimental catchment

The Baru experimental catchment (5°01′N, 117°48.75′E) is located in the East Malaysian state of Sabah on the northern tip of Borneo Island. This catchment is in the headwaters of the 2450 km^2 Segama catchment, which flows into the Sulu Sea. The catchment receives an annual rainfall of 2712 mm (σ: 435) (1986–1999: Bidin and Chappell, 2003) with very little seasonality in the regime (Chappell et al., 2001). The catchment is underlain by a relatively impermeable melange comprising mostly of mudstones, though small fissure related springs can be seen during unusually dry periods. The USDA Ultisol soil order of the Baru, equivalent to the FAO Alisol-Acrisol groups, is specifically a Haplic Alisol (Chappell et al., 1999b). Measurements indicate that soil permeability declines exponentially to a depth of 3 m (Chappell et al., 1998), and 'natural soil piping' is present at some locations within the catchment (Chappell and Sherlock, 2005). The altitude of the catchment ranges from 171 to 255 m, with much local relief (Fig. 1). Valley cross-sections are typically V-shaped, with very few reaches having wide, saturated valley-floor areas. This was supported by the lack of all but a few pockets of hydromorphic soils within the valley bottoms (Chappell et al., 1999b). The catchment has a high drainage density of perennial channels (6.5 km km^{-2}: Chappell et al., 2006), with the region having a very high channel density of 20–22 km km^{-2} when intermittent and ephemeral channels are also included (Walsh et al., 2006). The non-perennial channels are almost all ephemeral (storm-only) channels, as there is little of the rainfall seasonality that gives the intermittent flow regimes. The wet evergreen vegetation at this locality has an upper canopy dominated by *Parashorea malaanonan*, *P. tomentella* (both White Seraya), *Shorea johorensis* (Red Seraya) and *Rubroshorea* spp. (Marsh and Greer, 1992).

The Baru forest cover was disturbed by the first phase of commercial selective logging in 1988–1989 when 79.9 m^3/ha of timber was extracted. The catchment lies within Ulu Segama Forest Reserve, which is managed by the state forestry organisation called 'Yayasan Sabah'. Buffer zones were used within this logging coupe, where timber extraction and skidder vehicle use is prohibited, but it would seem not on the perennial streams less than 5 m width (Chappell, pers. observation). The 5 m threshold before stream buffers are defined is used elsewhere in South East Asia, Australia and Oceania (Cassells et al., 1984; Sist et al., 1998), but for areas of West Malaysia's rainforest, all perennial streams require buffers (MTCC, 2001; Thang and Chappell, 2004). Indeed, others suggest that intermittent and ephemeral channels should be buffered from commercial forestry activities (Bruijnzeel et al., 2004). Forestry within the Baru catchment has left 25 m ha^{-1} of gravel-surfaced haulage roads, 16 m ha^{-1} of un-surfaced, feeder roads and a further 61 m ha^{-1} of skid trails (Chappell et al., 2006). At a few localities, these roads and trails connect to the channels and thereby extend the network of ephemeral channels.

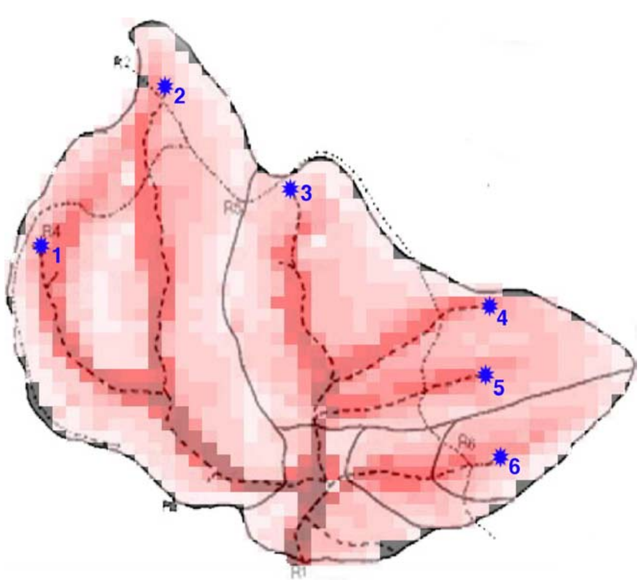

Fig. 1. The Kirkby topographic index mapped across the 0.44 km^2 Baru catchment, Malaysian Borneo (5°01′N, 117°48.75′E) where low values have a light shading (min. 5.99 ln(m)) and high values a dark shading (max. 12.99 ln(m)). The broad, dashed lines show the perennial channel network and the numbered perennial channel heads are shown with asterisks. The sub-catchment area of each perennial stream gauging structure is shown with a solid line, and the raingauges with the letter 'R' (see Chappell et al., 2004b). The secondary and feeder roads are shown with a dotted line.

2.3. Huai Pacha experimental catchment

The Huai Pacha experimental catchment (18°34′N, 98°10′E) is within the headwaters of the 3853 km^2 Mae Chaem catchment in Northern Thailand, which itself feeds the 120,693 km^2 Chao Phraya river which flows into the Bay of Bangkok. The Huai Pacha catchment lies close to the Mae Ning raingauge (18°37′N, 98°13′E) which received 1573 mm of rainfall in the study year, 2001. Rainfall in this region is received mostly during the northern hemisphere summer months, with the first few months of each calendar year normally receiving no rainfall (Dairaku et al., 2000; Boochabun et al., 2004). The catchment is underlain by granite, granodiorite and diorite (Royal Forestry Department, 2001). Measurements on undisturbed soil cores extracted from topsoil at two slope and two stream-side locations in the Huai Pacha catchment showed a narrow range of topsoil permeability of 31–54 cm h^{-1}, that is still much higher than typical rainfall intensities (Vongtanaboon, 2004). The altitude of the catchment ranges from 1230 to 1290 m (Fig. 2; Royal Forestry Department, 2001). The main valley cross-section has a wider valley floor in comparison to the Baru catchment, and a much lower drainage density of perennial channels of 4.8 km km^{-2}. Despite this, extensive areas of hydromorphic soils (e.g., FAO Gleysols or USDA Aquents) were not seen within the valley floors. The dry evergreen vegetation at this locality includes the climax vegetation of dry dipterocarp forest, but has been heavily disturbed by shifting cultivation by hill tribes (Uparasit and Isager, 2001). There is no visual evidence of buffering of the forest along the channels.

3. Methods

3.1. Overview

The aim of this study is to examine return-flow by examination of: (a) the location of channel heads, and (b) the patterns of topsoil moisture, both in relation to patterns in

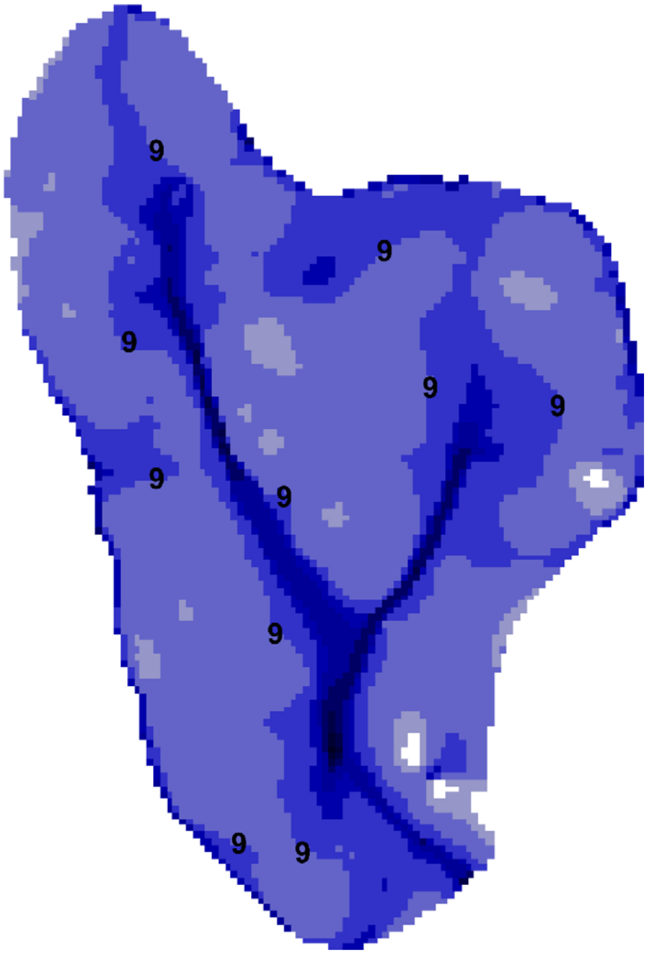

Fig. 2. The Kirkby topographic index mapped across the 0.21 km^2 Huai Pacha catchment, Northern Thailand (18°34′N, 98°10′E) where low values have a light shading (min. 2.23 ln(m)) and high values a dark shading (max. 17.27 ln(m)). The λ9-isoline is marked with symbol '9'. The perennial channel is located in the centre of the linear zones of high index values, and is shown in Fig. 4 with a solid line.

'Kirkby topographic index', λ (Kirkby, 1975; Beven and Kirkby, 1979). Derivation of topographic maps and then the λ-maps, are, therefore, central to both approaches. The channel head evaluation study was undertaken within the Baru catchment (Malaysian Borneo), in part because the relatively high drainage density (cf. Gregory, 1976) which gives six channel heads per 0.44 km^2 for evaluation, while the patterns in soil moisture were monitored and evaluated within the Huai Pacha catchment (Thailand), with its 1 m × 1 m Digital Terrain Model (DEM). The results from both catchments are then used to consider buffer zone definition aided by our experience of tropical streamflow generation processes and via consideration of published 'hydrological buffer studies' (e.g., Bren, 1995, 1998, 2000; Bonell and Molicova, 2003; McGlynn and Seibert, 2003; Thang and Chappell, 2004).

3.2. Derivation of the topographic maps

The topographic map of the 0.44 km^2 Baru catchment was derived from two key sources. All perennial and intermittent channels, those ephemeral channels at the head of each first-order (perennial) channel, and all contributory area divides were first mapped with a compass-and-chain survey in a closed-loop traverse (Kukuon and Hanapi, 1996). These data were then supported by more intensive closed-loop traverses of the channels and slopes using a TC400 Total Station (Leica Geosystems AG, Heerbrugg, Switzerland; Samat et al., 2001).

For the 0.21 km^2 Huai Pacha catchment, the topographic map or Digital Terrain Model (DTM) was derived from a 1 m × 1 m resolution digital database provided by the Royal Forestry Department. This map was supplemented by a ground survey of the location of channels and local terrain features.

3.3. Calculation of the Kirkby topographic index

The Kirkby topographic index for the Baru and Huai Pacha catchments were calculated using the multiple-flow-direction (MFD) algorithm of Quinn et al. (1995). The MFD algorithm is still considered to be the most accurate for topographic index calculation (Pan et al., 2004). The original resolution of the topographic data was used for the index calculation, i.e., 1 m × 1 m and 20 m × 20 m for the Huai Pacha and Baru, respectively.

3.4. Channel mapping (Baru)

With the maps of the channels in the Baru catchment (Kukuon and Hanapi, 1996; Samat et al., 2001) observations of the head-ward extent of the streamflow within the channels was routinely monitored during the 1996–2004 period (and supported by irregular observations in the 1990–1995 period). The visual observations were also supported by the construction and continuous monitoring of 14 gauging structures within the Baru catchment (Chappell et al., 1999a, 2004b). The most upstream point on the channel that always had streamflow was defined as the head of the perennial channel (i.e., head of the first-order channel; above which is the zero-order basin: Dingman, 1994; Bidin et al., 1993). These points are shown with asterisks in Fig. 1.

3.5. Topsoil moisture mapping (Huai Pacha)

The volumetric water content (m^3 m^{-3}) of the upper 0–0.15 m of the mineral soil profile in the Huai Pacha catchment was measured at 468 locations using a simplified time-domain-reflectometer (TDR) probe (Gaskin and Miller, 1996). A geometric sample spacing of 1–100 m was used, as this is required for subsequent geostatistical modelling (Journel and Huijbegts, 1978). The exact location of these topsoil moisture sampling points was geo-referenced to the topographic map using a theodolite. Previous research has indicated that topographic control on the lateral migration and downslope accumulation of soil moisture is greatest during wet periods (e.g., Grayson et al., 1997; Western et al., 1998). Such periods should also be the priority for understanding streamflow generation processes and rainfall-runoff model behaviour, given that most streamflow is generated at these times. As the

Huai Pacha catchment, like the Mae Chaem catchment as a whole, has the highest rainfall, runoff and moisture status in the month of August (Boochabun et al., 2004; Croke et al., 2004; Schreider et al., 2004; Vongtanaboon, 2004; Vongtanaboon and Chappell, 2004), the spatial survey of topsoil moisture was undertaken in August 2001.

To compare the map of the topographic index (Fig. 2) with topsoil moisture observations, the point measurements of moisture need to be interpolated across the Huai Pacha catchment. This interpolation is most accurately achieved by calculating an experimental semi-variogram, fitting a model to the observed spatial structure and then using kriging to derive the soil moisture surface (Nielsen and Wendroth, 2003). Strictly, the semi-variogram corresponds to half the expected value of the squared difference of the variable (here topsoil moisture) at two points, i.e.:

$$\gamma(h) = \frac{1}{2N(h)}\sum_{ij}(\theta_i - \theta_j)^2$$

where $\gamma(h)$ is the semi-variance; $N(h)$ the number of pairs of data in a given lag bin; θ_i and θ_j the volumetric soil moisture values at points i and j, respectively; and the summation is conducted over all i, j pairs in the lag bin (Journel and Huijbegts, 1978). Once modelled, the interpolated surface is then produced using ordinary kriging (Journel and Huijbegts, 1978; Nielsen and Wendroth, 2003). Within this study, the Easykrig 2.1 geostatistics programme (Chu, 2001) running on the Matlab platform (The MathWorks Inc., Natick, MA, USA) was used.

4. Results

4.1. Perennial channel head identification (Baru)

Fig. 1 shows that the perennial channel network and the perennial channel heads plotted over the Kirkby topographic index for the Baru catchment. The value of the topographic index for the 20 m × 20 m pixel containing each channel head location is shown in Table 1. The topographic index within the Baru catchment ranges from 5.99 to 12.99 ln(m) (Fig. 1), which is comparable to the range for other small catchments (e.g., Chappell and Franks, 1996). All channel head locations are within the range of 7.59 ln(m) (P2 north stream in Chappell et al., 2004b) to 8.75 ln(m) (P2 northeast stream in Chappell et al., 2004b; see Table 1; Jiang, 2004), and all perennial channels within the range 7.59–12.99 ln(m) (Figs. 1 and 3).

Table 1
Value of the Kirkby topographic index, λ, for each head of the perennial (first-order) stream channels within the 0.44 km^2 Baru catchment, Malaysian Borneo (5°01′N, 117°48.75′E)

Perennial channel head location	Stream name[a]	λ
1	P3 west	8.2816
2	P3 east	8.2802
3	P2 north	7.5875
4	P2 northeast	8.7515
5	P2 east	8.3800
6	P4	8.7130
Mean	All P1 perennial streams	8.3323

[a] Chappell et al. (2004b).

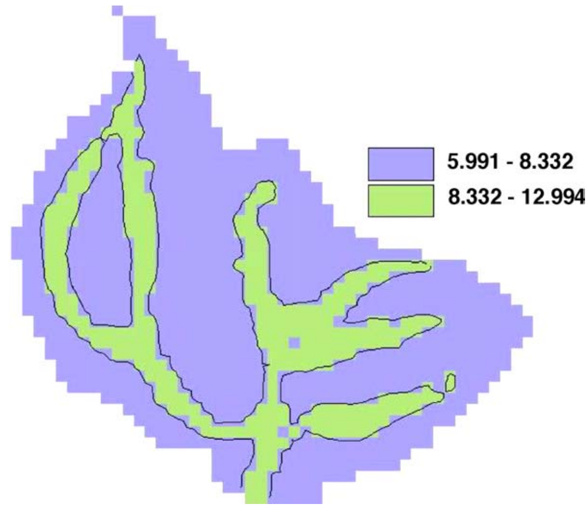

Fig. 3. Areas of the 0.44 km^2 Baru catchment (Malaysian Borneo) where the values of the Kirkby topographic index are either greater than 8.33 ln(m) or less than 8.33 ln(m). Compare with perennial network shown in Fig. 1.

Comparison of Figs. 1 and 3 shows that the most upstream point where return-flow is continuously delivered (i.e., within inter-storm as well as within-storm periods) is well defined. The arithmetic mean topographic index value for the perennial channel heads is 8.33 ln(m), and all perennial channel heads are less than two DTM pixels (i.e., 2 × 20 m lengths) away from the point on the channel at this value (Fig. 1). Channels where the head of the permanent channel flow is upstream of the λ value of 8.33 could be caused by the influence of one or more of the following in comparison to the other zero-order basins: (a) shallower porous media (i.e., the rock-head is closer to the ground surface), (b) a greater degree of convergence of the rock-head (cf. Hewlett, 1982) in comparison to the ground surface convergence (Freer et al., 2002), and (c) localised development of gleying and associated reduced permeability at only these perennial channel head locations.

4.2. Topsoil moisture mapping and prediction (Huai Pacha)

The 468 topsoil moisture values collected within the Huai Pacha catchment on 9 August 2001 conformed to a normal distribution (Vongtanaboon, 2004). Soil moisture data typically conform to a normal distribution (Nielsen et al., 1973; Chappell and Franks, 1996). The centroid of this distribution, the arithmetic mean ($\langle\theta\rangle$), was 0.415 m^3 m^{-3}, while the range was 0.138–0.572 m^3 m^{-3}, the variance 0.008 (m^3 m^{-3})^2, and the coefficient of variation (CV) 21.4%. During the fieldwork, the values of soil moisture in excess of approximately 0.50 m^3 m^{-3} were associated with patches of surface ponding, presumably indicating the presence of topsoil saturation and return-flow, and also the likely porosity of much of the topsoil within the catchment. The presence of locations near to the downstream section of the catchment with less than 0.25 m^3 m^{-3} volumetric

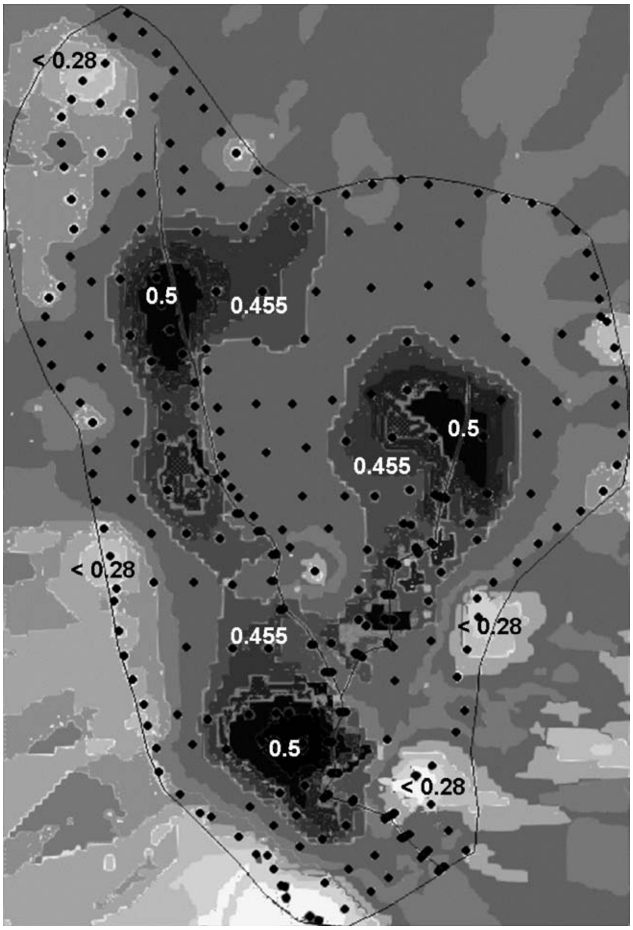

Fig. 4. Topsoil moisture content ($m^3\ m^{-3}$) within the 0.21 km^2 Huai Pacha catchment (Northern Thailand) on 9 August 2001. The map is based on 468 TDR measurements interpolated using kriging and a spherical model fitted to the experimental semi-variogram. The perennial channel is shown with a solid line.

moisture content (Fig. 4) only a few hours after 30 mm rain-event (Vongtanaboon, 2004), indicates a very well drained (permeable) soil profile, at least in these areas. This finding is consistent with the very limited data-set of topsoil permeability values for the catchment. The CV of 21.4% over an area of 0.21 km^2 is comparable to the 29.8% CV recorded in the nearby 0.042 km^2 Huai Daf micro-catchment, which is on the same geology (Vongtanaboon, 2004). Indeed, it is also similar to the 30.5% CV derived from 99 topsoil moisture values recorded on a similar Ultisol soil in the Ular rainforest micro-catchment in Brunei (Chappell, 2001). Such a variability, is also similar to that in soil moisture within Cambisols in the humid temperate Slapton Wood Catchment, UK (CV 26%: Chappell and Franks, 1996) and a 3.7 ha semi-arid gully catchment, central Spain (CV 25–49%: Fitzjohn et al., 1998).

The total of 468 soil moisture values collected in the Huai Pacha catchment is relatively small for reliable variogram construction, but is similar to the sample sizes used in, for example, Western et al. (1998), Western and Blöschl (1999) or Williams et al. (2003). The experimental semi-variogram for these data is presented in Fig. 5. A range of models was fitted to these data, and the model with the smallest root mean square

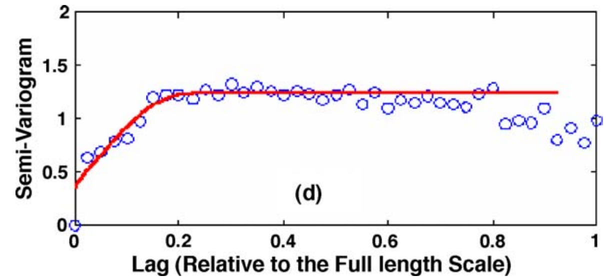

Fig. 5. Experimental variogram for the topsoil moisture content ($m^3\ m^{-3}$) within the 0.21 km^2 Huai Pacha catchment (northwest Thailand) on 9 August 2001. The solid lines show the best fit spherical model.

error (RMSE) was the spherical model (Fig. 5). The model indicates a range of 89.4 m and thus a correlation length of 30 m, a sill of 1.240 $(m^3\ m^{-3})^2$, and a nugget variance of 0.353 $(m^3\ m^{-3})^2$. The resultant spherical variogram model is thus:

$$\gamma(h) = 0.353 + 0.887\left[\frac{3}{2}(89.4) - \frac{1}{2}(89.4)^3\right]$$

The nugget variance of as much as 28% of the sill probably indicates that the minimum separation distance between the sampling locations (i.e., 1 m) may be too large for this area. The correlation length is the distance over which the soil moisture measurements are correlated. The correlation length for the Huai Pacha catchment of 89.4 m is relatively low given the spread of micro-catchment values of 20–300 m reported by Western et al. (2004). Some of the spread in correlation length estimates is caused by differences in the degree of average catchment wetness at the time of the spatial sampling. Table 2 compares the correlation lengths associated with each sampling episode with the Fitzjohn et al. (1998) study, which reports very low moisture contents and correlation lengths. These illustrative results suggest that as the average moisture content of the catchment increases, so does the correlation length. Thus, as the Huai Pacha catchment dries in the winter months, less and less structure is likely to be seen in the soil moisture patterns.

Statistical correlation (Pearson's product moment) of the gridded soil moisture data collected during the wet summer period (i.e., $\langle\theta\rangle = 0.415\ m^3\ m^{-3}$) in the Huai Pacha catchment with the gridded topographic index and when squared, gives only a very weak coefficient of determination (R^2) of 15%.

Table 2
Correlation lengths and average moisture content of the topsoil ($m^3\ m^{-3}$) observed by Fitzjohn et al. (1998) and by the Huai Pacha study

Date	Average moisture content ($m^3\ m^{-3}$)	Correlation length (m)
Fitzjohn et al. (1998), 3.68 ha gully catchment, central Spain		
14 September 1995	0.077	6.1
8 September 1995	0.123	6.2
30 January 1996	0.285	17.0
This study, 20.9 ha Huai Pacha catchment, northwest Thailand		
9 August 2001	0.415	89

The Spanish catchment is used for comparison as it is likely to experience as wide a seasonal range in soil moisture as in Northern Thailand.

Comparison with published studies indicates that in some micro-catchments around the world the topographic index explains more than half of the variance in the topsoil moisture or capillary potential (e.g., Grayson et al., 1997; Western et al., 1998). Other studies have, however, shown much less than half of the variance in soil moisture being explained by variance in the topographic index (e.g., Burt and Butcher, 1985; Chappell and Franks, 1996; Crave and Gascuel-Odoux, 1997). Weak correlations can be caused by spatial variations in rock fracturing, soil depth and permeability along the catena, or aspect differences in evapo-transpiration. Clearly, in such circumstances utilisation of a catchment model which excludes data on soil or rock characteristics will give unreliable simulations of spatial patterns of soil moisture content (or deficit), though this may not affect the ability to predict the streamflow response (Franchini et al., 1996). More importantly, comparison of the topographic index with measured patterns of soil moisture informs us of the simplicity (high R^2) or complexity (low R^2) of the subsurface system in the studied micro-catchment (Chappell and Franks, 1996).

Visual examination of the areas of topsoil with high soil moisture content (e.g., >0.455 $m^3\ m^{-3}$ or ca. >90% saturation) shows a very patchy distribution (Fig. 4). This is emphasised by the areas of relatively dry soil ($\leq$0.28 $m^3\ m^{-3}$) seen at some locations close to the perennial channel (Fig. 4). This contrasts with continuity of zones of high topographic index (i.e., high soil moisture accumulation) along the course of the same perennial channels (Fig. 2). Western et al. (1998) similarly noticed a more patchy topsoil moisture distribution in comparison to the well-connected, linear features predicted by topographic indices. Again, it is the reason for the discrepancy, rather than the discrepancy itself, that is more important.

The patchiness of wet soils within the Huai Pacha, which do tend to be in near stream areas, rather than near divide locations, but poorly correlated with topographic index at a pixel scale, might be caused by six different reasons:

(1) The rock-head could be closer to the ground surface in these wet areas, thus forcing more of the subsurface flow to the near-surface soils. Great local variability in depth of granite weathering and the presence of massive boulders within saprolite is known within tropical environments (Thomas, 1974); and at certain sections of the channel, granite boulders are exposed (Vongtanaboon, pers. observation).
(2) It is possible that the wet zones are associated with accumulations of the translocated clays produced by granite weathering. Such accumulations are commonplace within granite terrain (Thomas, 1974).
(3) Some catenal development of soils is seen with changes in soil colour within the Huai Pacha catchment. Changes in soil type and hence permeability (Chappell and Ternan, 1992; Elsenbeer, 2001) have been shown to affect soil moisture patterns within other micro-catchments, with more slowly permeable soils being wetter (e.g., Seyfried, 1998).
(4) If there are subsurface channels in the rock-head, due to preferential weathering within the granite (Campbell, 1997), then these could generate channels of preferential flow, known as 'percolines' (Bunting, 1961). These percolines may not have much surface expression, but may focus subsurface water to a point.
(5) If fractures in the granite are oriented towards the wet zones (Meju et al., 2001), then these would bring more water than predicted by the surface-derived, topographic index.
(6) Natural soil pipes are present with Ultisol soils at several sites throughout the tropics (Baillie, 1975; Jones, 1986, 1990; Chappell and Sherlock, 2005). Our experience from the Ultisol on the Baru catchment and the granite-derived Ultisol at Bukit Timah, Singapore, is that these underground tunnels often have very little surface expression and can be missed without intensive survey (Chappell and Sherlock, 2005). If the Huai Pacha catchment does contain natural soil pipes, then these might converge at certain points along the perennial channels, and so provide some explanation for the patchiness of the wet zones.
(7) At least partly due to errors in the Digital Terrain Model (Gyasiahyei et al., 1995) or calculation of the Kirkby topographic index (Pan et al., 2004).

Further field investigations, notably geophysical studies (e.g., Meju et al., 2001) would help identify which of these factors are locally the most important. The critical point being that the evaluation of the topographic index against measured soil moisture patterns should be seen as the starting point for further investigations into the nature of the soils and geology of a research catchment, rather than a final study.

5. Implications for streamflow generation processes in rainforest headwaters

The similarity of the Kirkby topographic index values at perennial channel head locations in the Baru indicates that topography (as opposed to or in addition to soil or geological variations) exerts a strong influence on the location of return-flow within the Baru catchment. Within the Huai Pacha catchment, visual observation of wet topsoil patches in near stream areas combined with a small amount of explanation in the coefficient of determination of 15% indicates that topography may exert an observable, but only partial control on return-flow locations within the Huai Pacha catchment. Further, the patchiness of the wet areas indicates that phenomena such a variable depth to rock-head, catenal variations in permeability (Chappell and Ternan, 1992), fracture flow or natural soil piping might have significant influence in this particular catchment. Indeed, the patchiness of wet zones in valleys below planar slopes has been observed by the authors in other micro-catchments, e.g., Slapton Wood catchment, UK (Chappell and Franks, 1996). Thus other micro-catchments with tropical Ultisol soils may (or not) show a similar level of subsurface complexity and require investigation. Examination of the soil and geological controls in the Huai Pacha catchment is a key question for our ongoing studies.

The second issue arising from the soil moisture observations within Huai Pacha catchment is that most of the topsoil in the catchment is relatively dry only a few hours after the monitored large storm in the wet season. This was also seen within a nearby 0.042 km^2 agricultural catchment (Vongtanaboon, 2004). Furthermore, previous research using tensiometers and piezometers within the equatorial Baru catchment showed that in all but valley bottom or channel head areas, the topsoil remained less than saturated even during large storms (Sherlock, 1997; Chappell and Sherlock, 2005). This was also seen within granite catchments on Singapore Island (Sherlock et al., 1995, 2000) and Peninsular Malaysia (Noguchi et al., 1997). These sites are not normally subject to the intense rainfalls associated with cyclonic storms (Bonell et al., 2004) which may produce extensive topsoil saturation (Bonell et al., 1981). Thus, away from cyclonic regions, tropical catchments can produce very fast stream responses (Bidin and Greer, 1997; Chappell et al., 1999a) without extensive topsoil saturation. Chappell et al. (1998) would suggest that pressure-waves and natural soil pipes, rather than saturation overland flow, are more important mechanisms to explain fast stream responses within these environments. This does not mean that these wet areas are not important water-pathways within such tropical catchments.

Given the proximity of zones of saturated topsoil to the permanent streams, any local disturbances to these wet soils during forestry or agricultural operations would directly impact on the perennial streams. Indeed, Chappell et al. (2004c) show that perennial channels deliver much more suspended sediments per unit area in comparison to ephemeral channels, most probably because they always carry water to detach and transport the soil/sediment. Thus areas away from these permanent channels are naturally buffered by the lack of a surface hydraulic connection. Clearly, the manipulation of the rainforest landscape by the addition of forestry roads may increase the surface hydraulic connection of slopes with permanent channels where roads cross the water courses (see Wemple et al., 1996; Croke and Mockler, 2001; Ziegler et al., 2001; Chappell et al., 2004b, 2006; Sidle et al., 2004).

6. Implications for use and improvement of topographically driven catchment modelling in rainforest headwaters

This pilot work on channel head and soil moisture evaluation of topographic indices that underpin several catchment models shows that such topographic indices can capture some of the controlling factors of the rainfall-runoff processes within tropical catchments. The patchy nature of near-saturated soils within streamside areas, as seen in the Huai Pacha catchment, does, however, indicate that topography alone may be insufficient to characterise the spatial distribution of rainfall-runoff processes within micro-catchments. Indeed, where measurements of soil moisture (or capillary potential) within an experimental catchment indicate different patterns to those of a topographic index, then field campaigns of geophysical measurements (e.g., Meju et al., 2001) need to be utilised to map the changing depth to rock-head, soil permeability, fracture patterns, etc. Such information may then be incorporated into a revised soil-topographic index (Pellenq et al., 2003; Lyon et al., 2004).

Clearly, more studies that evaluate topographic indices with spatial patterns of soil moisture or potential are needed within tropical rainforests or on tropical soils, to assess the likely reliability of such indices. Where ephemeral channels have clear starting points, one could examine whether there are similar values of the topographic index at these locations. This would also allow evaluation of whether the index could be used to estimate ephemeral channel head location or ephemeral channel extent (see Moore et al., 1988). Indeed, new studies ought to evaluate the predictive capabilities of a range of different topographic indices (see Campling et al., 2002b) in addition to the Kirkby index (Kirkby, 1975) examined here.

Within our pilot study, we examined the soil moisture patterns at only one time. Further tropical studies should address the dynamics of such patterns during dry periods, 'typical storms' (see the studies of Grayson et al., 1997; Western et al., 1998 in temperate latitudes) and during much larger events, e.g., those with 10-year return periods. There are very few studies that have mapped the extent of soil saturation during such 'extreme events' that produce the over-bank flows that damage livelihoods and cause human fatalities. The geostatistical characteristics derived by this pilot study (e.g., correlation lengths, sill and nugget variance) could be considered as estimates and should not be generalised across all tropical Ultisols. These estimates could be used as preliminary values to judge the likely 'spacing', 'extent' and 'support' (cf. Western and Blöschl, 1999) for these new soil moisture mapping studies in tropical Ultisol soils.

7. Implications for 'hydrological buffer' definition in rainforests

Buffer or protection zones can be designated along streams for many different environmental reasons (Bren, 2000; Bonell and Molicova, 2003; Broadmeadow and Nisbet, 2004). There are two direct hydrological reasons:

(1) Where saturated soils with 'saturation overland flow' occur near to stream channels, then eroded sediments or nutrients mobilised within or entering these areas will rapidly enter the stream and thereby have the potential to cause damage to local or downstream fauna.
(2) Wet soils have a lower shear strength and greater erodibility (Bryan, 2000), making them intrinsically more sensitive to disturbance by forestry vehicles. Thus, preventing disturbance to these wet streamside areas or preventing materials entering these very sensitive areas, has a much greater beneficial effect than protecting similarly sized areas elsewhere in catchment.

While our focus is on hydrologically defined buffer zones, the other reasons for buffer definition should be mentioned, as there maybe indirect hydrological effects, via restricted access or limited canopy disturbance:

(1) In agro-forestry or agricultural areas where sediment delivery to streams is more diffuse in comparison to areas with road landslides or point inputs at road bridges, then densely vegetated buffers may be used as 'filters' to trap sediments (Wallbrink and Croke, 2002; Ziegler et al., 2006a,b).
(2) Maintaining tree cover along stream banks (within a protected buffer) can help maintain natural stream temperatures, and thereby help sustain fish habitat (Pusey and Arthington, 2003).
(3) Corridors of undisturbed native trees along the streams can help maintain the seed-pool to help regenerate selectively logged forest on the adjacent slopes. These same corridors of undisturbed native trees also allow easier migration of ground and canopy dwelling fauna (Laurance and Laurance, 1999).

Within managed natural forests in the tropics, arguably the greatest potential hydrological impact along perennial streams results from 'ground skidding' (primary transportation) and haulage road construction (secondary transportation: Chappell et al., 2004c; Thang and Chappell, 2004). Ground skidding is the common method of transporting timber from tree stumps to the haulage lorries in commercial rainforests of SE Asia (Thang and Chappell, 2004). The tracks or wheels of these vehicles disturb soil, as do logs hauled behind the skidder. Keeping such vehicles and activities out of the wet streamside areas prevents what would be a disproportionate negative impact on the associated stream.

If we consider the map of soil moisture within the Huai Pacha catchment, then the area to be protected would be the areas of near-saturated and saturated soil (i.e., >90% saturated) and the stream itself (see Figs. 2 and 4), if the aim is to prevent trafficking of wet terrain. If infiltration-excess overland flow is not significant within the catchment (cf. Bonell, 2004), then protection of these wet zones may be considered sufficient for surface hydrological buffering. Depending on the catchment, the lateral extent of soil saturation may be relatively stationary (as in the deeply incised Baru catchment) or very dynamic, changing significantly through storm periods (see e.g., Anderson and Kneale, 1980). For an annual logging coupe (Conway, 1982), at least the saturated area for a storm with a 1-year return period should be defined as the minimum size of the 'hydrological buffer zone'. This definition might be considered problematic, given that extreme storms (e.g., the 10-year or even 100-year storm) have a disproportionate impact on erosion, mass movement and sediment transport (Douglas et al., 1999; Chappell et al., 2004c). Thus, it might be argued that the extent of the saturated area during the 10-year or even 100-year storm should be mapped and used to define the minimum size of the buffer zone. As it is often difficult to access rainforest terrain during such events, this suggestion would seem impractical, but worthy of further research.

Road construction is an integral part of the logging of primary rainforests. These roads comprise of primary and secondary (lorry) haulage roads, are often gravel-surfaced in a high timber-producing region such as Malaysia (Forest Department Peninsular Malaysia, 1999). There are also unsurfaced, feeder roads for lorry access within each annual logging coupe (op. cit.). Where primary transportation is by ground skidding (rather than cable yarding), skid trails then extend out from the lorry haulage roads. The haulage roads and most used skid trails become compacted by vehicle use, giving reduced near-surface permeability (Van der Plas and Bruijnzeel, 1993) and thereby increasing the likelihood of 'infiltration-excess overland flow' (Horton, 1933) being generated (e.g., Ziegler et al., 2001). If this infiltration-overland flow runs off the road onto ostensibly undisturbed slope soils at some distance from streams, the water will infiltrate and any carried sediment deposit on the slopes. This phenomenon is quite common within managed rainforest catchments (Chappell et al., 2004b; Sidle et al., 2004). Given that haulage roads are normally constructed along the contour, while streams run at a tangent to the contour, the haulage roads must cross the streams. At these crossings, the infiltration-excess overland flow generated on roads could short circuit any buffer zones defined by return-flow and soil saturation, and shed water and any carried sediments or chemicals into the stream. An obvious solution is to direct surface-water from forestry roads into drains and then to ensure that these drainage channels regularly shed their water onto natural slopes well away from stream channels. Ziegler et al. (2006b) have provided a very useful modelling methodology that could be used to define how large these natural slopes would need to be to consume all of the water and/or sediments from the upslope road drains, although they caution that even very large buffers may not be sufficient to allow infiltration of concentrated overland flow from roads, particularly during heavy rainfall. Thus, while the stream buffer will have haulage roads crossing, the road drains must not cross the buffer.

In some terrains, the construction of forestry haulage roads has exacerbated slope instability. Within the Baru catchment, high pore water pressures during some storms has led to large landslides which extend from road-fill materials to the streams (Chappell et al., 1999a,b, 2004b; Walsh et al., 2006). In terms of the sediment budget of a catchment recovering from the road construction and harvesting impacts, these landslides can be by far the largest source of sediment transported through the main stream gauging structure (Chappell et al., 1999a, 2004b). If buffer zones had been defined on all perennial streams within the Baru catchment, they would have offered little protection against these particular episodic pulses of sediment and water. These landslides started in roads that were correctly (see MTCC, 2001) constructed close to the catchment divide as practicable (i.e., just downstream of channel head 6 in Fig. 1), but only 1–30 m upslope from the perennial stream. Thus, in this terrain, the buffers might offer protection against surface-wash on roads transporting sediments to streams during the logging-phase (Douglas et al., 1999), but not protect against sediment inputs from landslides during the recovery-phase.

Pragmatic issues need to be considered when defining hydrological buffer zones. It took 9 h to measure the 468 soil moisture values within the 0.21 km^2 Huai Pacha catchment, and thereby estimate the spatial variability and extent of soil saturation (cf. Western et al., 2004). Clearly, to suggest that a tropical forest management company should map soil moisture across each annual logging coupe of say 10–50 km^2 (using the Ulu Segama Forest Reserve in Sabah as an example) as the basis for defining their buffer zones would be totally impractical (though the data would be very interesting to the hydrologist!). While estimates of topsoil moisture within semi-arid areas (Taylor et al., 1997) can be derived from satellite-based sensors, these approaches currently have insufficient accuracy to sample soil moisture patterns beneath dense tropical rainforest (Entekhabi et al., 2004).

As many large forest management companies operating in tropical countries use digital terrain data and Geographic Information Systems (GIS) at resolutions similar to our topographic analyses in the Baru catchment, topographically defined buffer zones would be feasible. Within the Baru catchment, a hydrological buffer zone could be defined for all areas with a threshold λ-value of 8.33 ln(m) or greater (for a DTM with a 20 m $\times$ 20 m resolution). While the pattern of λ remains similar as the DTM resolution changes, the absolute value of λ changes several ln(m) units (Woods and Sivapalan, 1997). This zone above this threshold would include all perennial channels (Fig. 1; Jiang, 2004) and all soils known to saturate during frequent storms (Chappell et al., 1998; Chappell pers. observation; unpublished borehole records). This same threshold might be expected to hold for the rest of the 2262 ha 'Coupe-89' that contains the Baru (Moura-Costa and Karolus, 1992), given the similar terrain, geology and rainfall. However, one would expect that the λ-value associated with the perennial channel head locations and the extent of the saturated soils would vary with geology (notably permeable versus impermeable rocks), mean soil depths and rainfall (where higher rainfall would give rise to a greater degree of catchment saturation). Observations of perennial channel head location are perhaps easier than extensive soil moisture mapping exercises conducted at one time or several times during the year. Thus, we suggest that new tropical rainforest studies are needed that would examine the relationship between perennial channel head location and topographic index values across a range of rainfall, terrain and geological settings. Perhaps optimistically, it may be that such analyses could be used to adjust threshold λ-values for regional geology, regional rainfall, etc. If so, objective buffer zones could be defined and maps produced that could be used by forest rangers to mark out the buffer zones in the field, or forest officers or certifiers to check that the 'hydrological buffer zones' remain undisturbed after regional forestry operations.

Other topographic indices (see e.g., Campling et al., 2002b) should be evaluated if this regional scale analysis were to take place, as there is still much debate as to which is the most appropriate index for definition of 'hydrological buffer zones' (Bren, 2000; Thang and Chappell, 2004). We do, however, comment that Bren (2000) found that the alternative index based on plan curvature had severe limitations for buffer zone definition.

The observation that most of the Huai Pacha catchment was much less than saturated just after the large, wet-season storm examined, is something that has also been seen in micro-catchments in West Malaysia (Noguchi et al., 1997), Singapore (Sherlock et al., 1995, 2000), Brunei (Dykes and Thornes, 2000) and East Malaysia (Kuraji, 1996; Sherlock, 1997; Chappell and Sherlock, 2005). These observations may suggest that topsoil outside of streamside areas does indeed remain much drier than the streamside areas and thereby is less sensitive to soil disturbance. This supports that idea that most of the soil protection should be located in the streamside areas in the form of buffer zones.

The patchiness of the wet zones along the perennial channel within Huai Pacha catchment has very significant implications for buffer zone definition. If all of the near-saturated and saturated soil (i.e., >90% saturated in August 2001) within Huai Pacha catchment were to be included within a fixed-width buffer zone defined by the topsoil moisture measurements, then a buffer with a fixed-width of 80 m either side of the channels would be needed to include all near-saturated areas (Fig. 4). This buffer area would cover 74% of the catchment. As near-saturated and saturated soil (i.e., >0.455 $m^3 m^{-3}$ which equates to >90% saturation) occupied only 6% of the whole catchment, or 23% of an 80 m wide buffer, then such a fixed-width buffer would be unnecessarily large (if degree of saturation were the only criteria being used).

If the topographic index were to be used to define the buffer width, a λ-value of greater than 9 ln(m) would contain almost all of the saturated soils observed (cf. Figs. 2 and 4). Such areas occupy only 31% of the whole catchment, and, therefore, considerably less than that of the 80-m fixed-width buffer. The topographic index does, however, define the crest slopes or catchment divides as areas likely to saturate due to their shallow slopes. These areas might be hydraulically unconnected to the wet valley soils and channels (see Fig. 2). Wet crest-slope soils may not, therefore, require protection. Within the Huai Pacha catchment, the crest-slope soils occupy 22% of the catchment that has a λ-value of greater than 9 ln(m), and thus 7% of the whole catchment. If the Kirkby topographic index were to be used to define buffer width, then an additional threshold term of distance from the permanent channels would need to be incorporated to exclude flat crest slopes. Alternatively a new topographically based index could be sought (see Campling et al., 2002b).

Most sustainable forest management guidelines, e.g., the Malaysian Criteria and Indicators, or MC&I (Thang, 1987; Thang and Chappell, 2004), require that buffer zones are defined for perennial channels, but not for intermittent (seasonally dry) and ephemeral (storm-only flows) channels. Our earlier work supports this separation. First, perennial streams within the Baru catchment generate much more suspended sediment per unit area in comparison to the intermittent and ephemeral channels (Chappell et al., 2004b). Second, if ephemeral channels were required to have buffers, because the drainage density of tropical catchments on Ultisols is typically high (e.g., Gregory, 1976; Walsh, 1996), the buffer zones would occupy most of the catchment area, thereby making reduced-impact forms of selective logging, uneconomic (Tay, 1999; Thang and Chappell, 2004). This could force many companies into very poor practices to provide timber to markets with no demands for sustainably produced timber, or encourage more clearfelling of natural forests. We appreciate that these are debateable points and others have different views (see e.g., Bruijnzeel et al., 2004).

While we consider that we have a pragmatic view, the practice of only defining buffers along streams that have a channel width of over 5 m (Cassells et al., 1984; Sist et al., 1998), omits many first-, second- and even third-order stream channels (Thang and Chappell, 2004). These streams do generate significant sediment yields per unit area (Chappell et al., 2004a,b) and consequently should be protected. Indeed, none of the streams within the Baru or Huai Pacha would be protected with this 5 m threshold. The importance of small perennial streams is further supported by work on streamflow generation in the 62 km^2 Lookout Creek forest catchment, USA. This work indicates that only 8% of streamflow is generated by return-flow into channels greater than third-order (i.e., fourth- and fifth-order: Wondzell, 1994). Again, this emphasises the need to buffer all first-, second-, and third-order channels in forested catchments. Buffering of all perennial streams within managed rainforests is feasible for large forestry concerns given: (a) the necessary topographic data are available and given that (b) some field validation of the locally appropriate λ-threshold is undertaken (Thang and Chappell, 2004). Encouraging and facilitating 'hydrological buffering' of small perennial streams has the potential to have considerable in-stream benefits (via restricting sediment inputs to channels), while leaving access to commercial timber resources.

8. Conclusions

The first objective of this study was to see if the heads of perennial channels within a tropical rainforest micro-catchment were located at consistent topographic locations. From our analysis of the location of perennial stream heads in the 0.44 km^2 Baru catchment (East Malaysia), we found that these could be predicted by the Kirkby topographic index (λ spatial distribution) to within two 20 m × 20 m terrain pixels in this basin. Thus, within this area topography plays a key role in the generation of perennial streams. Indeed, more explicit analysis of stream networks and topographic characteristics within future forest hydrology studies in the tropics would also aid our understanding of the runoff processes within near-stream areas (cf. Woods and Sivapalan, 1997).

The second objective of this study was to examine the pattern of moisture content within the topsoil of a tropical rainforest micro-catchment during the wet season, and see how well this is predicted by the Kirkby topographic index (Kirkby, 1975; Beven and Kirkby, 1979). A spatial structure of 468 soil moisture content measurements within the 0.21 km^2 Huai Pacha catchment (Northern Thailand) was identified by variogram analysis and this was used to interpolate the data. A patchy distribution of near-saturated and saturated soils was observed along the perennial streams. Further, the λ spatial distribution was poorly correlated with the whole moisture data-set (R^2 = 15%), which indicates the need to characterise soil-geological variability in addition to topographic factors, to precisely identify areas of return-flow within this catchment. Thus the assumption of a dominance of the topographic control on soil moisture made by most TOPMODEL studies does not hold for this catchment in Northern Thailand. The wet patches did, however, coincide with areas of high topographic convergence and with values of the λ spatial distribution greater than 9 ln(m), indicating some explanation is afforded by the topographic index. To date, there has been very limited validation of such internal-state processes and parameters of topographically based hydrological models under tropical conditions, with the exception of Molicova et al. (1997), Chappell et al. (1998) and Vertessy and Elsenbeer (1999). Many more validation studies should be undertaken with tropical (rainforest) data. Such studies would also generate new data-sets of soil moisture and other return-flow controls and thereby add to our knowledge of tropical runoff mechanisms.

The last objective of this study was to draw implications of our new findings on the location of return-flow within two tropical rainforest micro-catchments for the definition of 'hydrological buffer zones'. The comparison of the perennial channel head locations with values of the λ spatial distribution, indicated that this index may be useful in locating the perennial stream network on digital maps for objective 'hydrological buffer zoning'. Further, the work that located the near-saturated soils and compared these zones with the λ spatial distribution, showed that the wet zones did coincide with areas of high topographic convergence and with values of the λ spatial distribution greater than 9 ln(m). Use of this threshold in the λ spatial distribution, rather than a fixed-width buffer that includes all areas of saturated soil (at the time of sampling), defined smaller protection zones, with a higher proportion of the sensitive, near-saturated soils. As a consequence, the λ-based buffers would be more efficient, easier to justify scientifically, and allow access to more of the timber growing on less sensitive, drier soils. Clearly, such conclusions are preliminary and require evaluation in a wide range of tropical rainforest catchments before the findings can be generalised. While uncertainties in the predictions of buffer zones with the λ spatial distribution will always remain given the complexity of soils and geology across the tropics, use of an index which identifies buffer zones on first-, second-, and third-order streams (as well as larger streams) must be considered more environmentally acceptable than systems which limit buffers only to those streams wider than 5 m. Given the extent of tropical rainforest currently managed for commercial timber production (let alone converted to plantations or agro-forestry), this research is required urgently.

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