Available online at www.sciencedirect.com
SCIENCE DIRECT®
Forest Ecology and Management 224 (2006) 58–80
Forest Ecology and Management
www.elsevier.com/locate/foreco

BARUMODEL: Combined Data Based Mechanistic models of runoff response in a managed rainforest catchment

Nick A. Chappell [a,*], Wlodek Tych [a], Arun Chotai [a], Kawi Bidin [b], Waidi Sinun [c], Thang Hooi Chiew [d]

[a] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[b] Universiti Malaysia Sabah, 88999 Kota Kinabalu, Sabah, Malaysia
[c] R&D Division, Yayasan Sabah, 88817 Kota Kinabalu, Sabah, Malaysia
[d] Forestry Department Peninsular Malaysia, 50660 Kuala Lumpur, Malaysia

Abstract

The impact of different forestry practices on headwater streams in the wet tropics is a serious environmental concern. Despite this, there are very few experimental catchment studies that quantify the hydrological impacts of specific tropical forestry operations. While new field studies are imperative, more could be gained from existing catchment studies by extracting information from the available time-series. Data Based Mechanistic (DBM) models can be used to extract hydrological information from such time-series by fitting a range of Transfer Function models using the simplified recursive instrumental variable (SRIV) algorithm and without a priori assumptions about the water pathways. An optimal model and its associated hydrological system parameters are then identified from objective statistical measures (e.g. R_t^2, YIC) and only then by selection of that model with the most plausible physical explanation. While the DBM method has been applied to the relationship between rainfall input and streamflow output in tropical rainforests, it has never been used to simultaneously examine the relationships within rainfall–streamflow data and the component water pathways of overland flow, subsurface flow and transpiration. Modelling these component pathways is important to the understanding of likely changes in the rainfall–streamflow behaviour resulting from tropical forestry. We aim to show the value of our multiple component DBM models to simulate the sensitivity of stream behaviour to different densities of skidder vehicle trails within a managed rainforest in Borneo.

The first application of DBM modelling to the component water pathways of an equatorial rainforest catchment shows that the overall rainfall–streamflow response is flashy, with a residence time of 36.25 ± 0.19 min, when compared to other small catchments, but on minor aquifers. The overall response is, however, much less flashy in comparison to the infiltration-excess overland flow pathway which has a residence time of only 5.50 ± 0.09 min. The overland flow pathway is also less non-linear in its response in comparison to the subsurface pathway and overall response. A new DBM model of transpiration was found, and was similarly shown to give a rapid dynamic response to the input variable, in this case air temperature. The DBM approach indicated that higher order models (e.g. multiple subsurface pathways) were not statistically identifiable within any of the high frequency, 12-month time-series modelled. The first application of DBM modelling to land use/change scenarios in the same equatorial rainforest catchment suggested that the majority of the stream behaviour, in a period 7-years after selective logging, is insensitive to the skid trail densities associated with reduced impact logging (RIL) or clearfell systems in Malaysia. This is largely because of the relative insignificance of the overland flow pathway and the fact that changes in this pathway are predicted to occur on the rising stage of stream hydrographs, rather than at the more critical peak. While controversial, this result is consistent with our previous findings which show that some forestry impacts on hydrology are exaggerated in the popular perception.

Keywords: DBM model; Peakflow; Skid trail; time-series data; Transfer function; Tropical forestry

1. Introduction

1.1. Value of hydrological time-series data from managed tropical rainforests

There are many popular perceptions about the hydrological impacts of logging natural forests in the wet tropics (Bruijnzeel, 2004; Chappell, 2005), yet there are very few quantitative

* Corresponding author. Tel.: +44 1524 593933; fax: +44 1524 593985.
E-mail address: n.chappell@lancaster.ac.uk (N.A. Chappell).

0378-1127/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2005.12.008

time-series data on which to base management decisions (Bruijnzeel, 1990, 1992, 2001; Chappell et al., 2004b; Thang and Chappell, 2004). The spatial variability of the natural water-pathways combined with the patchwork of impacts of selective commercial forestry requires that significant change to the hydrological system must be examined at an integrated scale (Chappell et al., 2004b). To a hydrologist, this level of integration is the 0.1–50 km^2 scale of the 'experimental catchment' (Gregory and Walling, 1973). Thus, changes to the magnitude and timing of water-flow must be seen in the hydrograph of a stream draining at least 0.1–50 km^2. Similarly, if impacts of a particular forestry practice on water-related phenomena such as nutrient or sediment losses are to be quantified, this must be observable at the 0.1–50 km^2 scale. Spatial variability is too great to attempt extrapolation of micro-scale observations (<0.001 km^2 or 0.1 ha) to the whole landscape. Where changes are observed at the experimental catchment scale, then local investigations may be needed to link a particular forestry practice or forestry-related landform with the catchment-scale impact. The extreme dearth of catchment-scale studies addressing the hydrological impacts of logging natural forests in the wet tropics (Chappell et al., 2004b) means that: (a) extrapolation of results across the whole of the wet tropics is unrealistic; and (b) more should be made of the existing time-series data—at least to identify priorities for new research studies.

1.2. Value of DBM models over models which have a priori assumptions about the hydrological system being modelled

Modelling can be used to: (a) extrapolate time-series results from case studies; and (b) identify key hydrological system parameters or dynamic response characteristics. Three classes of models that have been used to simulate the hydrological response of rainforest catchments are: (1) physics-based models; (2) conceptual models; and (3) Data Based Mechanistic models. Physics-based models of catchment hydrology solve many geophysical equations for the component water-paths within catchments, notably the Penman-Monteith Equation for evapo-transpiration, the Chezy-Manning equation for overland flow and the Darcy-Richards equation for subsurface flow (e.g. Bathurst et al., 2004; Ott and Uhlenbrook, 2004). Controversially, we would suggest that no experimental catchment (i.e. 0.1–50 km^2) in the wet tropics has sufficient data on soil/rock characteristics, soil depths, soil surface characteristics and canopy characteristics, to allow accurate physics-based modelling of distributed water pathways to be made (see e.g. Beven, 2000, 2001b, 2002; Chappell et al., 1998, 2004c; Chappell and Sherlock, 2005; Croke et al., 2004). Without reliable estimates of parameter values representative of the whole catchment, forest use/change predictions become unrealistic. Conceptual models make assumptions about the dominant hydrological processes operating and then use simplified equations to capture the hydrological dynamics. Such models include TOPMODEL (e.g. Chappell et al., 1998), TOPOG (e.g. Vertessy and Elsenbeer, 1999) and most applications of IHACRES (e.g. Croke et al., 2004). DBM models are different to both physics-based and conceptual models in that they make no a priori assumptions about the nature of the hydrological system, for example, the topographic control on soil moisture (Chappell et al., 2004b, this volume) or the dominance of two flow pathways (i.e. fast and slow: Croke et al., 2004). In contrast, DBM modelling identifies a range of simple mathematical relationships in the form of transfer functions (TFs) sometimes combined with simple non-linear sub-models, uses objective statistical criteria to reject some of these models and only after this, rejects further where they are shown to be inconsistent with a physics-based interpretation (Young, 2001; Young et al., 2004). To reiterate, while DBM is limited by the range of mathematical relations typically evaluated (e.g. only three non-linear components: Young, 2003), it does not have a priori hydrological assumptions, so that all identified models could be rejected if considered inconsistent with hydrological theory. DBM is also different from other data-based techniques (e.g. Camarasa and Tilford, 2002; Hundecha and Bardossy, 2004), in that it uses a very powerful method, the simplified recursive instrumental variable (SRIV) algorithm (Young, 1985, 1999, 2001), to identify the model structures and associated parameter values.

Over the past 20 years, many scientists have suggested that only physics-based catchment models should be used to simulate land cover/use change impacts, such as those associated with forestry (see e.g. Bathurst et al., 2004; Ott and Uhlenbrook, 2004). More recently, other scientists have, however, suggested that these physics-based catchment models may not be giving reliable results of hydrological change following forestry or other land cover/use change scenarios due largely to the large uncertainties in the calibrated parameter values (Parkinson and Young, 1998; Beven, 2001a,b; Beven and Freer, 2001; Chappell and Fowell, 2003; Chappell et al., 2004c). Models requiring calibration of a smaller number of parameter estimates thus giving smaller uncertainty have started to be used to simulate land cover/use change scenarios. These models, with their smaller numbers of parameters (called 'parsimonious models': after Box and Jenkins, 1970) include the conceptual models of Whitehead et al. (1998), Viney and Sivapalan (2001) and Croke et al. (2004). Thus far, the DBM modelling approach, which is also described as parsimonious, has not been used to simulate tropical forestry impacts on runoff response.

1.3. Tropical forestry impacts on runoff response

A key potential impact of tropical forestry on stream response is via water pathway changes resulting from the presence of vehicle tracks and roads (Chappell et al., 2004b). Within the tropical rainforests of Southeast Asia, the most common method of transporting logs from tree stumps to log landings is by ground skidding using tracked skidder vehicles (Thang and Chappell, 2004). These vehicles locally compact topsoil, reduce its permeability (Van der Plas and Bruijnzeel, 1993; Malmer, 1996) and can locally enhance the proportion of infiltration-excess overland flow (Baharuddin, 1995; Douglas et al., 1995; Chappell et al., 2004a,b). There are, however, so few reliable data on the proportion of net rainfall which generates infiltration-excess overland flow on skidder vehicle trails in tropical rainforests (Chappell et al., 2004b; Thang and Chappell, 2004). Indeed, we are only aware of the runoff plot data on infiltration-excess overland flow on skid trails produced by Baharuddin (1995) in Peninsular Malaysia, and those studies within the 4 km^2 Sapat Kalisun, which includes the 0.44 km^2 Baru catchment (Table 1; Chappell et al., 2004b; Thang and Chappell, 2004). Given that the Baru catchment and its surrounding area might be considered a reference site for rates of surface flow on tropical rainforest skid trails, more should be made of these available data.

We know what the combined response of surface and subsurface flows have on the response of the third-order Baru stream under the given forestry regime, as we have continuously gauged the flow of the stream at station P1 (Fig. 1: Chappell et al., 2004a). What we do not know, is how the overall stream response would have differed if a different density of skid trails (or other forestry features: Conway, 1982) had been used within the Baru. Different densities of skid trails are utilised with different forms of rainforest harvesting practiced in Malaysia, notably clear-felling, conventional selective logging and reduced impact logging (Pinard et al., 1995, 2000; Thang and Chappell, 2004). To our knowledge, there are no published modelling studies which show the individual effect of skid trail density on stream response within the wet tropics. The only study addressing the combined effects of a different skid trail density and a different degree of canopy disturbance for different types of selective rainforest logging in the wet tropics is the Bukit Berembun study in Peninsular Malaysia (Chappell et al., 2004b). The Water Erosion Prediction Project (WEPP) model has been used to examine the effects of road (and skid trail?) construction on surface and subsurface flow pathways on streamflow response, but for streams in temperate USA (Elliot and Tysdal, 1999; Rhee et al., 2004). We chose not to use this physics-based modelling approach to address possible skid trail impacts on streamflow response for our tropical catchment because of the issue of parametric uncertainty identified earlier. Instead, we will attempt the first DBM approach to modelling possible impacts of using different densities of forestry skid trails.

Table 1
Plot studies in the 4 km^2 Sapat Kalisun catchment (5°01′N, 117°48.75′E) near the Danum Valley Field Station (Malaysian Borneo), used to measure infiltration-excess overland flow on skid trails and natural slopes (disturbed and undisturbed)

Slope type	No. of plot replicates	Type of monitoring	Reference
Skid trail	1	Volumetric	Sinun et al. (1992)
Disturbed cover	3		
Undisturbed		3	
Skid trail	1	Volumetric	Douglas et al. (1995)
Haulage road drainage	1	Datalogged tipping-buckets	Chappell et al. (1999, 2004a), this study
Skid trail	1		
Disturbed cover	3		
Undisturbed	2		

The 0.44 km^2 Baru catchment is located in the northern headwaters of the Sapat Kalisun.

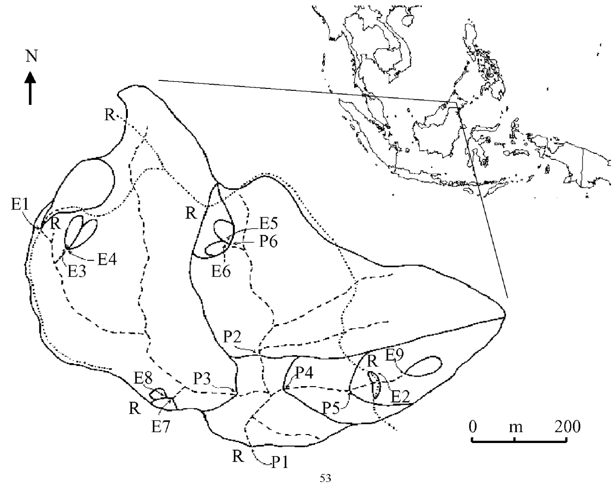

Fig. 1. The 0.44 km^2 Baru rainforest catchment (5°01′N and 117°48.75′E) located on the north-eastern tip of Borneo Island in Southeast Asia. The boundaries of the contributory areas (solid lines), the perennial streams (dashed lines) and lorry haulage roads (dotted lines) are shown. Contributory areas are labelled at their outlet and gauging location. Raingauge locations are shown with the symbol 'R'. River gauging stations on channels with perennial flows are shown with the symbol 'P', and those on channels with ephemeral flows are shown with the symbol 'E'.

1.4. Aims and objectives

The aims of this work are to demonstrate the hydrological information that can be extracted from high quality time-series data (i.e. the value of collecting such data) at the catchment and local scales, the hydrological interpretation of dynamic response characteristics (DRCs) of different hydrological pathways, and the utility of existing time-series data in predicting the hydrological effects of tropical forest change, all using DBM modelling. The four specific objectives designed to meet these aims were:

(1) To identify the relationship between catchment-average rainfall and streamflow for a 0.44 km^2 humid rainforest catchment and the associated parameters (i.e. DRCs).
(2) To identify the possible structure and parameters of component hydrological pathways (i.e. infiltration-excess overland flow, subsurface flow and transpiration) of the same catchment through DBM modelling of the streamflow (and subsurface flow) signal, and the first DBM modelling of representative local-scale measurements of overland flow and transpiration.
(3) To combine the component DBM models into a single, multiple pathway model, that is consistent with observations and the catchment-average rainfall–streamflow model.
(4) To use simple gain terms representing a long-term, measured or predicted runoff coefficient for each water pathway (at a representative local scale) to assess the effect of differing skid trail density on streamflow via changes to the extent of infiltration-excess overland flow.

The importance of fully utilising high quality, hydrological time-series data to understand the behaviour of our managed, equatorial catchment is stressed throughout. Indeed, this is the first study to combine DBM modelling of rainfall–streamflow time-series with representative local scale hydrological time-series, and then explicitly utilise the results in scenario modelling of humid tropical forestry.

2. Research catchment and time-series data available

2.1. Equatorial rainforest site and forestry management

The modelling presented here is based on time-series data and hydrological experience gained from the 0.44 km^2 Baru Experimental Catchment in Sabah, Malaysian Borneo (Fig. 1, 5°01′N, 117°48.75′E: see Sinun et al., 1992; Chappell et al., 1999). The catchment is less than 2 km northeast of the Danum Valley Field Centre (DVFC), a research station managed by the Research and Development Division of Yayasan Sabah, in collaboration with research organisations such as the Universiti Malaysia Sabah and the Royal Society of London. Yayasan Sabah (YS) is a state forestry organisation that manages a 9728 km^2 timber concession which is some 14% of the East Malaysian State of Sabah. Forestry research within this region has addressed the effects conventional tractor logging on sediment delivery (Douglas et al., 1992), the effects of reduced impact logging (RIL) on carbon budgets (Pinard et al., 1995), the viability of enrichment planting in disturbed natural forest (Moura-Costa et al., 1996), and the effects of post-logging recovery on sediment delivery and canopy hydrology (Chappell et al., 2001, 2004a). Environmental conservation is also a major objective of YS. This is shown by their gazetting of three large tracts of undisturbed natural forest as protected conservation areas; these are the 438 km^2 Danum Valley Conservation Area, the 588.4 km^2 Maliau Basin Conservation Area and ca. 300 km^2 Imbak Canyon Conservation Area.

The Baru Experimental Catchment (Fig. 1) was subject to the first phase of commercial selective logging in 1988/1989. The history of logging operations in the Baru is shown in Table 2. A combination of D8 tractor skidders and highlead yarding was undertaken, and a yield of 79.9 m^3/ha of timber was harvested from the encompassing annual coupe (Moura-Costa and Karolus, 1992). Given the dearth of hydrological studies on selection felling, the Baru may have become the only hydrological reference catchment in the wet tropics for such forestry operations outside of those in Peninsular Malaysia (Chappell et al., 2004b).

2.2. Hydrological time-series data available

Within this article we use time-series data on catchment water-paths collected during the water year 1st July 1995 to 30th June 1996 (see Chappell et al., 1999), a period some 7-years after road construction and timber harvesting of previously virgin rainforest (Table 2). The time-series are obtained by field sampling at 10 s intervals and modelling after integration to 5 min intervals, giving 105,408 values per time-series. Such a high resolution is required given the flashiness of the streams in the Baru catchment (Chappell et al., 2004b).

The gross rainfall input to the Baru catchment was measured with 103552D tipping-bucket raingauges (Casella CEL Ltd., Kempston, UK) monitored by Newlog dataloggers (Technolog Ltd., Wirksworth, UK). Because of the high spatial variability of rainfall within the Baru catchment (Bidin and Chappell, 2003), catchment average rainfall (at each 5 min interval) was derived by applying the Thiessen Polygon method to the data from six gauges distributed across the Baru Catchment (R1–R6 in Fig. 1). Fig. 2a shows the time-series of catchment average rainfall for the Baru basin.

A gauging structure had been built to monitor the streamflow leaving the whole Baru catchment (P1 in Fig. 1). It comprises of a thin-plate, 120° V-notch weir which maintains sub-critical flow in an upstream stilling pool where a shaft encoder linked to a Newlog datalogger recorded water-level. The rating from water-level to streamflow was then derived from the relationship with spot measurements of discharge using dilution gauging (integration method) and current metering (mean-section method). Fig. 2b shows the time-series of streamflow monitored at station P1 in the Baru catchment for 1st July 1995 to 30th June 1996 period. The Baru catchment contains 14 sub-catchment areas, gauging a range of landscape elements from channel heads, slopes with infiltration-excess overland flow,

Table 2
History of the first phase of logging operations in the Baru Experimental Catchment, Ulu Segama Forest Reserve, Sabah, East Malaysia in 1988 and 1989

Date	Forestry operation
Prior to August 1988	Gazetting of Ulu Segama Forest Reserve for commercial forestry and inventory of timber trees within the undisturbed natural forest
August–September 1988	Secondary road and feeder road construction, including slope cutting, culverting and surfacing
28th December 1988	Start of Matahari clearance of trees from the road corridor (to aid road trafficability during logging), skidder yarding and highlead yarding at first mast
10–18th May 1989	Harvesting of timber in the eastern part of the Baru catchment
21st May 1989	Skidder logging plus installation of second highlead logging mast
25th May 1989	Second highlead mast in place in the western part of the Baru catchment
30th May–2nd Jun 1989	Highlead logging at second mast
June 1989	Further skidder yarding until end of June
July 1989–to date	Forest recovery phase, with forest biomass monitoring and designation as a research area

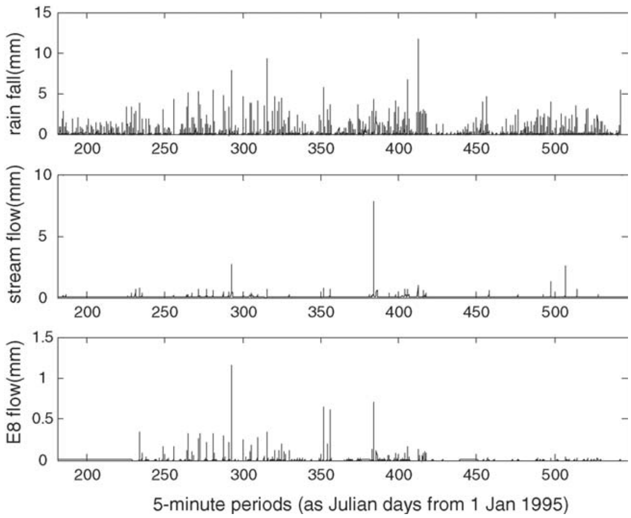

Fig. 2. Five-minute sampled time-series of water flow for the 1st July 1995 to 30th June 1996 water-year in the Baru catchment, where (a) is the catchment-average gross rainfall; (b) streamflow measured at station P1 (see Fig. 1); and (c) the infiltration-excess overland flow measured at site E8 (see Fig. 1).

skid trails, to road drains and road gullies (Fig. 1). The larger sub-catchment areas are similarly monitored with 120° V-notch weirs, while the smaller sub-catchment areas are monitored by using zinc-plates and a flume to guide surface flow in to large (ca. 3 l) tipping-bucket devices linked to Newlog dataloggers. Sub-catchment areas where infiltration-excess overland flow was monitored, were: (a) a lightly compacted, skidder-vehicle track (E4 in Fig. 1) draining an area of approximately 0.155 ha; (b) a section of haulage road that carries water that it intercepts from a stream (E1 in Fig. 1), (c) a slope section that carries surface flow when a road drain (E2 in Fig. 1) which intercepts a stream (from site E9) that overtops and flows downslope towards stream P4/5, (d) an ephemeral channel that receives surface flow from a skid trail during storms (E5 in Fig. 1), and (e) an area with an almost planar slope (lacking a channel, skid trail or road) that generates some infiltration-excess overland flow (E8 in Fig. 1). Fig. 2c shows the time-series of infiltration-excess overland flow monitored at site E8 from 1st July 1995 to 30th June 1996.

The location of the timber haulage roads generating overland flow within the Baru have been mapped by the Danum Survey Team using closed-loop traverses with a TC400 Total Station (Leica Geosystems AG, Heerbrugg, Switzerland; Fig. 1). These data are supplemented by: (a) a detailed survey of the skid trails within a 100 m wide corridor along 860 m of forestry road in the eastern half of the Baru catchment; and (b) a survey of road and skid trail width at 60 locations within the Baru.

The components of evapo-transpiration have been less well monitored in the Baru catchment in comparison to rainfall, streamflow, overland flow and a derived subsurface flow estimate. The only 5-minute transpiration data currently available for the Baru Experimental Catchment have been measured on five 15-year old camphor (*Dryobalanops lanceolata*) trees. These measurements were undertaken with TDP80 sapflow sensors (Delta-T Devices Ltd, Cambridge, UK), and together with air temperature, have been recorded using CR10 dataloggers (Campbell Scientific Ltd., Shepshed, UK). We have monitored rainfall below the forest canopy (i.e. net rainfall) in a 4 km^2 area including the Baru catchment using 500 storage raingauges and 5 tipping-bucket raingauges (Bidin, 2001; Bidin and Chappell, 2006). The 12-month average net rainfall estimated as a proportion of the rainfall received by the canopy (i.e. gross rainfall) has been calculated (Chappell et al., 2001) allowing a 5-minute time-series of net rainfall to be derived by multiplying the gross rainfall by this proportion. We could not calculate a 5-minute time-series of wet-canopy evaporation (i.e. that component of rainfall which evaporates from wetted leaves rather than reaching the ground) as we do not have measurements of canopy wetness (or canopy storage) over the several hours that the leaves remain wet after rainfall (cf. Bidin, 2001).

All of the time-series data pre-processing and then DBM modelling was undertaken within the Matlab programming environment (The MathWorks Inc., Natick, USA).

3. Methods

3.1. Method rationale and justification

All of the analysis used in this study used the Data-Based Mechanistic (DBM) modelling approach (Young, 2001). Within this approach the information contained within the dynamics of lumped input–output behaviour (e.g. rainfall–streamflow, or rainfall–overland flow and rainfall–subsurface flow) was used to define the structure and parameters of the model from a large range of possible options. Thus, a priori hydrological information is not required in the initial stage of modelling. This approach is consequently less constrained by possible misconceptions about the hydrological theory (see e.g. Klemes, 2000; Chappell, 2005) or the role of particular phenomenon (e.g. soil layers in generating shallow lateral flow, or an assumed role of Hortonian overland flow: Chappell and Ternan, 1992; Chappell et al., 1999; Sherlock et al., 2000; Chappell and Sherlock, 2005) than physics-based or conceptual models. As DBM model structures are much simpler or more 'parsimonious' than those of physics-based models, uncertainties in model predictions can be much reduced, and often more readily calculated (Parkinson and Young, 1998). DBM and some other data-based models (e.g. Croke et al., 2004) utilise transfer functions (TFs) to simulate runoff or water pathway dynamics. A first order TF, which has already been utilised to simulate the rainfall to streamflow relation of the Baru catchment (Chappell et al., 1999) takes the form:

$$Q(t) = \frac{P}{1 - \Re z^{-1}} R_{\text{eff}}(t - \delta) \qquad (1)$$

where $Q(t)$ is subsurface flow along the dominant pathway (mm) at time-step t; P the model production parameter; the recession term; R_{eff} the effective rainfall (i.e. rainfall corrected for non-linear soil-water storage effects); δ the pure time delay between the effective rainfall input and initial streamflow response; and z^{-1} the backward shift operator (Chappell et al., 1999).

The parameters P and can be used to derive the dynamic response characteristics (DRCs) of:

$$\text{ssP} = \frac{P}{1 - \Re} \quad (2)$$

$$\text{TC} = \frac{-t_{\text{base}}}{\log_e(-\Re)} \quad (3)$$

where ssP is the steady state production (or 'water-balance' term) and TC is the time constant or 'residence time', and t_{base} is the time base of the sampling (here 5 min) (Chappell et al., 1999).

Clearly, the robustness of any model structure and its parameters is dependent on the sophistication of the model identification/calibration routines (Box and Jenkins, 1970). There are two key sophisticated elements in model identification unique to DBM (and more recent applications of the related IHACRES), potentially making DBM more reliable than many other modelling techniques:

(1) Many models use least squares (LS) algorithms to find or calibrate model parameters. The problem with these LS methods is that the noise within time-series data gives rise to considerable bias and uncertainty in the model parameters (Young, 1984). With the DBM approach, model structure and parameter values are identified (or calibrated) by the simplified recursive instrumental variable (SRIV) algorithm. In the SRIV approach, time-series data are pre-filtered using the estimate of the dynamic recession filter after the initial LS estimate. This removes higher frequency observation disturbances focusing the signal in the useful frequency range where dominant dynamic modes of the system are contained. Following this step, the Instrumental Variable method with specially generated instruments is used, which removes the bias of the estimates. Both of these steps considerably reduce parametric uncertainty (Young, 1984, 1985, 1999, 2001).

(2) A second advantage of DBM over other data-based methods in particular comes from its use of the objective statistical measure of the Young Information Criterion (YIC) in the model and parameter identification/calibration:

$$\text{YIC} = \log_e \frac{\sigma^2_{\text{error}}}{\sigma^2_{\text{obs}}} + \log_e\{NEVN\} \quad (4)$$

The first term of YIC is a measure of the model efficiency, where σ^2_{error} is the variance in the model residuals and σ^2_{obs} the variance in the observed data, and the second term, normalised error variance norm (NEVN), is a measure of the degree of over-parameterisation (Young, 1985, 2001). Generally, as model complexity increases, so does the ability to capture more and more of the dynamics in the observed time-series, but at the expense of growing parametric uncertainty. There is, therefore, an optimum complexity (or 'model order') given that more complexity increases the uncertainty in the individual parameters identified. The YIC is a measure of whether the model has become over complex (i.e. too many parameters) given the amount of information contained within the observed data-series.

As a result, we consider that the DBM approach to modelling does not give more combinations of water pathways than is justified by the data, as can be the case with physics-based and conceptual models which require definition of water pathways prior to any modelling. The consequence of defining the most simple structure justifiable and by using a method which implicitly derives uncertainty estimates, DBM identifies parameters (or DRCs) of the pathways that have well defined values with quantified, small uncertainties.

3.2. Modelling stage I: DBM rainfall–streamflow response

The streamflow behaviour of a region is an integral of the interacting effects of several water pathways within a catchment, as such it is perhaps the most important hydrological time-series to measure and understand within a tropical rainforest (Chappell et al., 2004b). The first stage of this study, therefore, used DBM to identify the dominant structure and parameter values for the rainfall–streamflow response for the whole Baru catchment.

It is widely acknowledged that streamflow response is non-linearly related to rainfall input. The most widely accepted reason for non-linearity in catchment response is non-linear variations in the moisture storage within the subsurface unsaturated zone (Young and Beven, 1994; Chappell et al., 2004b). Within the DBM methodology, this non-linearity is typically modelled either using the Bedford Ouse Sub-Model (BOSM) or the Store Surrogate Sub-Model (SSSM) (Chappell et al., 1999, 2004a,b; Young, 2001, 2003). In this process the rainfall input is said to be transformed to an effective rainfall, R_{eff}, which is then linearly related to the streamflow response. For the analysis presented here, the Bedford Ouse Sub-Model (Chappell et al., 2004b; Young, 2001) is used. The generalised representation of BOSM for catchment response is:

$$R_{\text{eff}}(t) = R(t)\,\theta_{\text{cat}}(t) \quad (5)$$

where

$$\theta_{\text{cat}}(t) = \theta_{\text{cat}}(t-1) + \frac{1}{\tau_{\text{cat}}}\{R(t) - \theta_{\text{cat}}(t-1)\} \quad (6)$$

where R_{eff} is the effective rainfall (mm); R the gross rainfall (mm); $\theta_{\text{cat}}(t-1)$ the unsaturated zone storage variable at the previous time-step (mm); and τ_{cat} the dimensionless non-linearity term for the whole catchment response (Chappell et al., 2004c). The non-linearity term (τ_{cat}) is determined by an iterative process applied to the combined BOSM and TF sub-models, where the objective function is the Nash and Sutcliffe (1970) efficiency measure, R_t^2 (Chappell et al., 1999). The unsaturated zone storage variable (θ_{cat}) is calculated by setting the first value to zero. The time-series of effective rainfall is then normalised to give an ssP (Eq. (2)) equal to the runoff coefficient for flow pathway (e.g. Eq. (9)) using:

$$R_{\text{Neff}}(t) = R_{\text{eff}}(t)\left(\frac{\eta}{\sum R_{\text{eff}}(t)}\right) \quad (7)$$

where η is a normalisation term, thus giving a normalised effective rainfall, R_{Neff} (mm). Thus, the non-linear form of the DBM model of catchment response has five DRCs or parameters for a first-order model of the response, namely τ_θ, η, TC (or), ssP (or P) and δ. Only five model parameters is considerably less than 1000's of parameter values typically required by distributed, physics-based models, and consequently such DBM parameter sets are much better defined (Young, 2001; Chappell et al., 2004c).

The net rainfall is that proportion of the gross rainfall which reaches the ground by stemflow and (direct or indirect) throughfall (see e.g. Chappell et al., 2001). That component of the gross rainfall which does not penetrate the vegetation canopy, is stored and returned to the atmosphere by wet canopy evaporation. Within the Baru catchment, the lag between gross rainfall and net rainfall (due to temporary canopy storage) is typically less than 5 min (Bidin, 2001), i.e. less than one time step in the time-series data used within this paper, and thus not significant. From the large raingauge network of Bidin et al. (2003) that was monitored over one year, the net rainfall amounts to 86% of the gross rainfall. Thus, the net rainfall time-series is estimated from the formula:

$$R_{\mathrm{net}}(t) = \alpha R_{\mathrm{gross}}(t), \qquad \text{where } \alpha = 0.86 \tag{8}$$

where R_{net} is the net rainfall below the vegetation canopy at each 5 min time-step (mm); R_{gross} the gross rainfall above the vegetation or in large forest gaps (Chappell et al., 2001) at each 5 min time-step (mm), and α a gain term used to estimate the net rainfall from the gross rainfall. DBM models of the relationship between the catchment-average, net rainfall and streamflow were undertaken, as with the rainfall–streamflow modelling.

For this first stage of the modelling process, only the streamflow time-series and either the catchment-average rainfall or catchment-average net rainfall time-series are required, no additional information from local-scale measurements or other catchment-scale measurements are needed. The order of the model structure, for example, how many different water pathways clearly express themselves in the lumped rainfall–streamflow response was determined; with all possible combinations from first-order to fourth-order models being identified. While use of SRIV and *YIC* ensures that the model structure and parameters are robust, it is difficult to know how to modify the parameters of the model identified (i.e. τ_θ, ssP, TC and δ) to simulate the effects of a changing local or component phenomena resulting from a different degree of tropical forestry impacts. Thus, within the five subsequent modelling stages we seek to model, concurrently, the component phenomena.

3.3. Modelling stage II: DBM net rainfall–local overland flow response

At Danum, the proportion of the streamflow that is derived by infiltration-excess overland flow or ‘Hortonian Overland Flow’ (HOF: Horton, 1933), i.e. water which flows over the ground surface due to the rainfall intensity exceeding the infiltration capacity (or topsoil permeability) is less than 3% of the rainfall on average (Chappell et al., 1999, 2004b). This is because the local topsoil has a high permeability (Chappell and Sherlock, 2005), while the typical storm rainfall intensity is relatively low compared to tropical regions with cyclonic rainfall (Chappell et al., 2001; Bidin and Chappell, 2003, 2006). While it is commonly believed the tropical catchments have a high proportion of infiltration-excess overland flow, field measurements within most areas of the tropics (notably areas without extreme cyclonic rainfall) show that little of the streamflow is generated by infiltration-excess overland flow (Dubreuil, 1985; Bonell, 2004; Chappell et al., 2004b; Bidin and Chappell, 2006; Chappell, 2005).

Given that infiltration-excess overland flow generates such a small proportion of streamflow, it is likely that its contribution cannot be assessed by SRIV and subsequent partial fraction expansion of the DBM-modelled, stream hydrograph (Young, 1992). For the Baru catchment we do, however, have direct measurements of infiltration-excess overland flow, but at local scales. For this preliminary study, all of the time-series of infiltration-excess overland flow are examined and one selected as being representative of the time-series of infiltration-excess overland flow for the whole catchment.

Non-linearity may be apparent in the relationship between net rainfall and infiltration-excess overland flow, due to the variable effect of surface wetness and capillarity (Horton, 1933). Thus, we use the BOSM to examine the strength of the non-linearity in the infiltration-excess overland flow process. The form of the model follows that of Eqs. (5) and (6), except that R_{eff} and R are replaced by R_{OFeffnet} (the effective net rainfall that generates an overland flow response) and R_{net} (the net rainfall), respectively, while the non-linearity terms now relate to the wetness of the ground surface, and are given as $\theta_{\mathrm{sur}}(t-1)$ and τ_{sur}. The effective net rainfall generating subsurface flow is then normalised to give the same monthly input as the net rainfall, as in Eq. (7), giving a normalised effective net rainfall, $R_{\mathrm{NOFeffnet}}$ (mm). The order and parameters of the linear transfer function between the effective net rainfall and resultant infiltration-excess overland flow are then identified or calibrated with SRIV.

3.4. Modelling stage III: DBM net rainfall–subsurface flow response

As only 4% of the streamflow of the third-order Baru catchment is generated by overland flow, with 96% coming from subsurface flow pathways (Chappell et al., 1998, 1999, 2004b,c), the non-linearity (τ_θ) and residence time (TC) parameters in the rainfall–streamflow model will be largely a function of the subsurface flow behaviour. A subsurface flow time-series can be calculated by subtracting a representative infiltration-excess overland flow time-series from the time-series of the Baru streamflow.

Within this study, the relationship between the subsurface flow time-series and both the rainfall and net rainfall (see Eq. (8)) is identified. As with the infiltration-excess overland flow, the non-linearity is modelled using BOSM. The form of the model follows that of Eqs. (5) and (6), except that R_{eff} and R are replaced by $R_{\mathrm{SUBeffnet}}$ (effective net rainfall that generates a subsurface response) and R_{net} (the net rainfall), respectively, while the non-linearity terms now relates to the subsurface moisture, and given as $\theta_{\mathrm{sub}}(t-1)$ and τ_{sub}. The normalised effective net rainfall, $R_{\mathrm{NSUBeffnet}}$ (mm) is then generated by the same procedure as for the infiltration-excess overland flow or whole catchment response (see Eq. (7)). The order and parameters of the linear transfer function between the effective net rainfall and resultant subsurface flow is then identified or calibrated with SRIV.

3.5. Modelling stage IV: DBM temperature–local transpiration response

During the water-year 1995/1996, the Baru catchment received 2956 mm of rainfall and discharged 1867 mm of streamflow. Thus, the runoff coefficient (RC) for the Baru catchment, i.e.

$$\mathrm{RC} = \left(\frac{\sum Q}{\sum R}\right) \qquad (9)$$

where $\sum R$ is the annual catchment-average rainfall (mm) and $\sum Q$ the annual streamflow leaving the same catchment (mm), is approximately 0.63 (Chappell et al., 1999). With no major aquifers within the catchment and an assumption of no significant exchanges of groundwater across the catchment divides (see Chappell et al., 1999), the $\sum P - \sum Q$ value of 1089 mm, or 37% of gross rainfall, equates to the evapo-transpiration. Evapo-transpiration includes losses to the atmosphere by wet-canopy evaporation, transpiration and soil evaporation. Within a humid, well-vegetated rainforest environment, soil evaporation is assumed to be insignificant. Wet-canopy evaporation in the Baru has already been stated to be 14% of rainfall (i.e. $P_{\mathrm{gross}} - P_{\mathrm{net}}$ over a year: Bidin et al., 2003). Thus, the annual transpiration losses from the Baru catchment amount to approximately 675 mm or 23% of gross rainfall in the 1995–1996 water year (i.e. 37–14% of rainfall). This value is within the range of those observed within other managed, equatorial rainforests (Bruijnzeel, 1990; Kuraji, 1996) and is also quite a significant component of the catchment water balance, so it would be helpful to attempt to model its dynamics. We do not have a high-resolution time-series of transpiration averaged over the whole 0.44 km^2 Baru catchment. Such data can be derived from towers which extend well above the rainforest canopy (Moreira et al., 1997), so we hope to utilise a 100 m GAW tower recently constructed near to the Baru for these measurements in the future. Presently, the only high-resolution (5 min) data we have for transpiration comes from sapflow sensors installed within individual camphor (*D. lanceolata*) trees, all some 15-years old and 1 km southwest of the Baru catchment.

In order to simulate the dynamics of the transpiration pathway we sought to identify a new DBM model; air temperature were used initially as the input variable. These temperature data were manipulated in many ways before a dynamic DBM model between a manipulated temperature and transpiration time-series was identified. To allow the temporal dynamics of transpiration from a single tree ($E_{\mathrm{TRtree}}(t)$) to be used as an initial estimate of the catchment-average transpiration dynamics ($E_{\mathrm{TRC}}(t)$), the tree data were normalised using the difference in the annual average net rainfall and streamflow, i.e.

$$E_{\mathrm{TRC}}(t) = E_{\mathrm{TRtree}}(t)\left(\frac{\sum R_{\mathrm{net}}(t) - \sum Q(t)}{\sum E_{\mathrm{TRtree}}(t)}\right) \qquad (10)$$

3.6. Modelling stage V: linking components for subsequent scenario modelling

Thus far, our methodology has used DBM techniques to derive separate model structures and parameters for streamflow generation and related water pathways. Such separate analyses are important for understanding the dynamics of the whole streamflow generation system, but a greater integration of these component models might allow a new type of scenario modelling, namely robust identification/calibration of component DBM model structures from observed time-series, combined with a simple 'gain element' to link the components, which could be adjusted to reflect a forestry scenario. Within this fifth stage of the modelling process, hydrological understanding of the linkages between the component water pathways is essential. The key reason for linking these components is to allow the balance between specific components (e.g. infiltration-excess overland flow and subsurface flow) to be altered using hydrological experience from the local or related sites. This could allow the effect of specific forestry operations on the overall streamflow response to be examined simply via modification of the balance between different component pathways. This method has the very clearly expressed assumption that DRCs of each component pathway do not change with the land cover/use modification. For example, flashiness (i.e. TC) of the overland flow pathway or its sensitivity to surface moisture (i.e. $\tau_{\theta gs}$) does not change as the number of skid trails in an area changes as a result of different harvesting rates; only the amount of water moving along this pathway changes. This is unlikely to be true, but may be considered acceptable as a first approximation. This type of scenario modelling could have several advantages over scenario simulations with physics-based models. First, the initial or unchanged state of the system is based directly on the time-series data available for the catchment, rather than assumed relationships between small-scale physics (and associated parameters) and the water pathways (sometimes not even observed) (see Beven, 2001b; Chappell et al., 1998, 2004c). Second, allowing different forestry scenarios to be simulated by changes to the balance between different hydrological components (i.e. via a gain term) allows time-series observations of the relative importance of different pathways from other studies to be incorporated simply and clearly.

Within the example forestry scenario that follows, the key linkage is between the DBM model of net rainfall to infiltration-excess overland flow and that of net rainfall to subsurface flow. Once the two separate DBM models are derived from the observations, two gain terms are added to alter the magnitude of the input, one for each pathway:

$$R_{\mathrm{netOF}} = R_{\mathrm{net}}\beta \tag{11}$$

$$R_{\mathrm{netSUB}} = R_{\mathrm{net}}(1-\beta) \tag{12}$$

where

$$\beta = \left(\frac{\phi_{\mathrm{scenario}}}{\phi_{\mathrm{obs}}}\right) \tag{13}$$

$$\phi_{\mathrm{obs}} = \left(\frac{\sum Q_{\mathrm{OF}}}{\sum R_{\mathrm{net}}}\right) \tag{14}$$

and R_{netOF} is the component of net rainfall entering the non-linear infiltration-excess overland flow system; R_{netSUB} the component of net rainfall entering the non-linear subsurface system; ϕ_{obs} the annual proportion of net rainfall observed to generate infiltration-excess overland flow; ϕ_{scenario} the annual proportion of net rainfall observed to generate infiltration-excess overland flow set by the user to the observed value (ϕ_{obs}) or an alternative proportion of infiltration-excess overland flow for a forestry scenario; $\sum Q_{\mathrm{OF}}$ the annual total of infiltration-excess overland flow (mm); $\sum R_{\mathrm{net}}$ the annual total of net rainfall (mm); and β the scaling factor in the gain element to allow for a different balance of overland and subsurface flow.

The overall model comprising of the individual DBM model components linked by either: (i) a switch (between net rainfall to streamflow or net rainfall to component surface and subsurface pathways); (ii) a gain element (for infiltration-excess overland flow and subsurface flow); or (iii) an integrator (for transpiration), we call the BARUMODEL, after the catchment data-series used to develop the approach. A block diagram of the BARUMODEL is shown in Fig. 3.

3.7. Modelling stage VI: skid trail impact scenarios

Our first application of the BARUMODEL structure is in the assessment of the hydrological effects of a key tropical forestry operation, namely ground skidding (see Conway, 1982). We begin this work by reviewing the literature for the different densities of skid trail used within the wet tropics, notably within Malaysian rainforest. The second stage of the work attempts to utilise this information within the BARUMODEL. For the scenario modelling presented in this paper, we make preliminary assumptions that the non-linearity and flashiness of the overland flow system does not change under a different forestry system (e.g. clearfell, conventional selective logging and reduced impact logging) only the proportion of the water moving along this surface pathway changes. We know that this assumption is not fully valid, but need to make it before we can evaluate it in future work. We utilise the skid trail density information by simply changing the ϕ_{scenario} term and thereby the gain element β-term, to alter the split between infiltration-excess overland flow and subsurface flow.

4. Results: DBM model and parameter identification

4.1. DBM rainfall–streamflow response

The results of the DBM modelling of the rainfall–streamflow are shown in Table 3. To show the value or need for the non-linear transform of the rainfall to take account of the

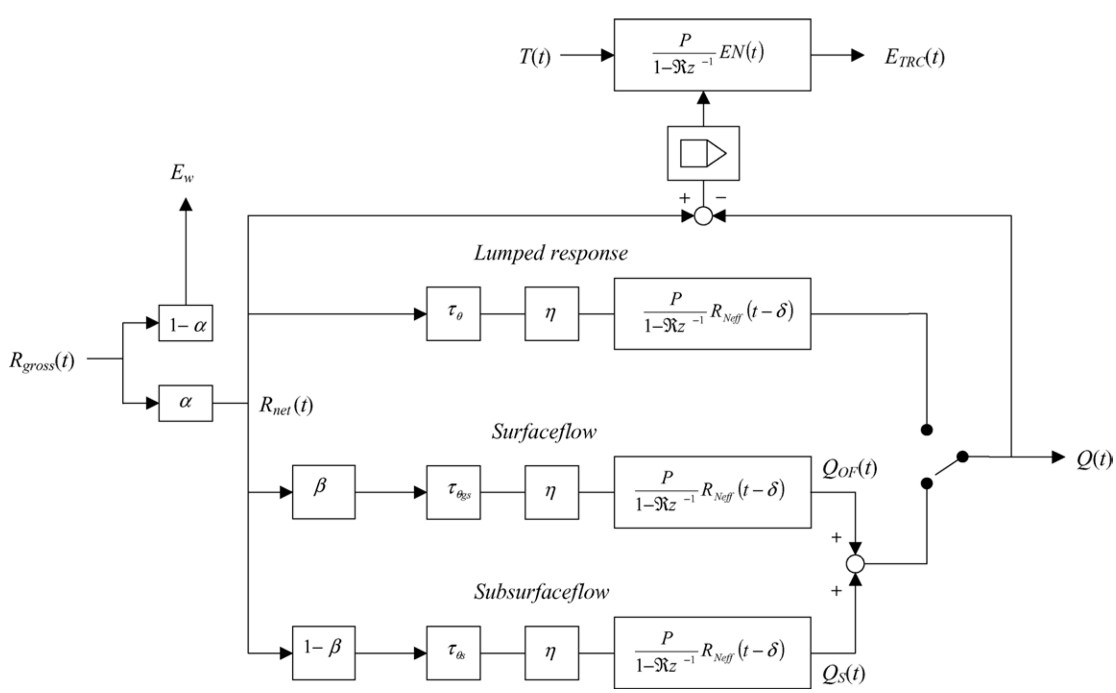

Fig. 3. A block diagram of the whole BARUMODEL.

Table 3
DBM model parameters identified for water pathways lumped at the third order Baru stream (5°01′N, 117°48.75′E) near the Danum Valley Field Station (Malaysian Borneo)

Parameters and statistics	DBM model		
	1	2	3
Structure	[1 1 2]	[1 1 3]	[1 1 3]
R_t^2	0.488	0.769	0.769
YIC	−11.141	−12.499	−12.499
τ	–	300	300
η	–	1438	1237
	−0.9678	−0.8739	−0.8739
σ()	0.0002	0.0005	0.0005
P	0.0246	0.0794	0.0923
$\sigma(P)$	0.0001	0.0003	0.0004
TC	152.55	37.10	37.10
σ(TC)	1.00	0.17	0.17
ssP	0.7618	0.6299	0.7323
RC*	0.630	0.630	0.733

Model 1: purely linear DBM TF model of gross rainfall to streamflow; Model 2: DBM TF with BOSM non-linear model of gross rainfall to streamflow; Model 3: DBM TF with BOSM non-linear model of net rainfall to streamflow. Structure: [No. of denominators, numerators, pure time delays]; R_t^2: Nash and Sutcliffe (1970) efficiency measure; YIC: Young Information Criterion (see Eq. (4)); τ: BOSM non-linearity term (see Eqs. (5) and (6)); η: normalisation term (see Eq. (7)); : recession term; σ(): standard deviation of the recession term; P: production term; $\sigma(P)$: standard deviation of the production term; TC: time constant (or residence time); σ(TC): standard deviation of the time constant; ssP: steady-state production (or gain) of the transfer function (TF); *RC**: observed input minus output of the pathway being modelled.

unsaturated zone storage effects, a purely linear transfer function model was first derived. This purely linear first-order model explains only 48.8% of the variance in the streamflow response with one P-value (hence one steady-state production) and one -value (hence one time constant) and three time-steps (i.e. 15 min) of pure time delay before the initial response (δ) (Table 3). By capturing the non-linearity using BOSM (Eqs. (5) and (6)), the first order model explained 76.9% of the variance in the streamflow response (Table 3), a significant improvement over the purely linear model. SRIV was used to calibrate the DBM model to 12-months of 5 min sampled data (water year 1st July 1995 to 30th June 1996). Given the time-series data has a 5 min time-step, the -value of—0.8739 $\pm$ 0.0005 for the non-linear model equates to a residence time or time constant (Eq. (3)) of approximately 37.10 $\pm$ 0.17 min. Thus, the uncertainty in this measure (given as one standard deviation, see Table 3) of the flashiness of the hydrological system is given. The uncertainty arises from a combination of noise in the rainfall and/or streamflow data (due to rainfall patchiness, errors in the gauging structure calibration, etc.) and limitations of the model structure to fully capture all of the dynamics of the system. Further, a time constant of 37.10 $\pm$ 0.17 min indicates a very flashy rainfall–streamflow response in comparison to other contributory areas modelled using DBM techniques (Table 4). A key comparison site is the 0.133 km^2 Bukit Berembun C1 catchment which is also in Malaysian rainforest and has a similar convective rainfall regime to the Baru (Bidin, 2001; Noguchi et al., 2003; Bidin and Chappell, 2003, 2006). The geology does, however, contrast markedly between the two sites and is probably the main reason for the difference in the flashiness (or time constant) of the two basins. The Bukit Berembun catchment is on a deeply weathered granite (i.e. saprolite) aquifer giving the more damped response (i.e. greater storage), while the Baru is one a relatively impermeable mudstone aquitard (Chappell et al., 2004b).

Higher order modelling with up to fourth order DBM models was undertaken. Many models converged, but showed too large a positive change in the YIC measure (Eq. (4)) from that of the first order model values or produced Impulse Response Functions with non-monotonic recessions (see Box and Jenkins, 1970). The first test is an indication of over-parameterisation of the model structure, while the second test is an indication of a model with oscillatory behaviour. All higher order models were, therefore, rejected, leaving only the first order model.

In order to show the effect of subtracting a fixed proportion of wet-canopy evaporation from the rainfall (Eq. (8)), the net rainfall to streamflow response was also modelled with the DBM approach. Table 3 shows that the DRCs of the non-linearity measure (τ_θ) and flashiness measure () for a first-order model do not change significantly from those of the gross rainfall–streamflow response (Table 3). To illustrate how much of the observed streamflow dynamics are captured, a short period of observed and simulated data are presented in Fig. 4. These data cover a storm with a return period of 10 years (Douglas et al., 1999; Chappell et al., 2004a). This model used a calibrated τ_θ-value of 300 (Eqs. (5) and (6), Table 3) and is shown in Fig. 5.

4.2. DBM net rainfall–local overland flow response

On all monitored slopes at Danum, except timber haulage roads and skid trails, annual mean infiltration-excess overland

Table 4
Time-constants (TCs), or 'residence times', for first order DBM models several small contributory areas ranked by area

Time constant	Catchment	Area (km^2)	TF model structure	Non-linear filter	Climatic regime	Media	Reference
14.5 min	Plot	0.000015	[1 1 0]	SSSM	Temperate	Acid soil	Fawcett et al. (1997)
23 days	C1	0.133	[1 1 0]	SSSM	Humid tropical	Saprolite	Chappell et al. (2004b)
37 min	Baru	0.44	[1 1 3]	BOSM	Humid tropical	Mudstone	This study
8.6 h	Coalburn	1.5	[1 1 0]	BOSM	Temperate	Mudstone	Chappell, unpublished
8.3 h	Bottoms	10.6	[1 1 1]	BOSM	Temperate	Limestone	Chappell, unpublished

Note that all DBM models shown use a Store Surrogate Sub-Model (SSSM: Chappell et al., 1999) or Bedford Ouse Sub-Model (BOSM: Eqs. (5) and (6)) to capture the initial non-linear response, but the differences in the TCs of the linear component resulting from using either model is very small.

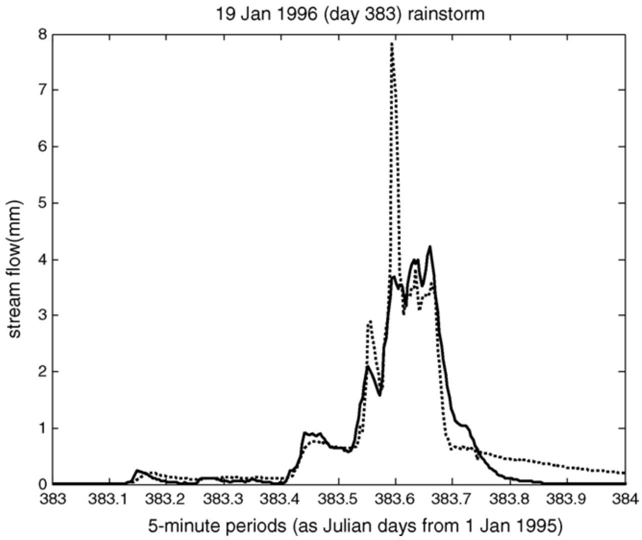

Fig. 4. Simulated DBM streamflow from net rainfall input together with observed streamflow of the 0.44 km^2 Baru catchment. The model is calibrated to a 12 month time-series sampled every 5 min (105,408 values per time-series), but shown for an example storm with a 10-year return period (i.e. 19th January 1996).

flow was less then 5% of the stream hydrograph (Sinun, 1991; Sinun et al., 1992; Chappell et al., 1999, 2004a). Only on very compacted sections of skid trails (made by the D8 skidders) near to haulage roads, were significant volumes of infiltration-excess overland flow generated (e.g. 52.5% at site 5: Sinun, 1991; Sinun et al., 1992). Indeed, on skid trails used for only a few tractor passes, e.g. site E4 (Fig. 1, equivalent to site 4TA in Chappell et al., 1999) infiltration-excess overland flow was only 2.4% of net rainfall. Overland flow was monitored on two haulage roads in the Baru catchment-site E2 and E1, and 4 and 62% of streamflow per unit area of catchment was generated (Chappell et al., 1999, 2004a). The flow at site E2 was caused by an upslope road drain over-toping, because the stream (E9 stream in Fig. 1) had not been culverted beneath this secondary haulage road. Similarly, the flow at site E1 was caused by the E1 stream not being culverted beneath the feeder road, so that the whole stream is diverted along the road. In both cases, significant volumes of overland flow are not generated by a local infiltration-excess mechanism, but by the roads intercepting and re-routing channel flow along their surface. Indeed, the length of the path taken by the channelized flow actually increased following re-routing of the flow along the road sections.

Given these varied results, the time-series of overland flow for site E4 is judged to best represent the overland flow dynamics for the whole Baru catchment, in this preliminary study. Further work modelling all of the overland flow time-series presented in Chappell et al. (2004a) is ongoing. By applying the DBM approach to the E4 data, a first-order transfer function is seen as the optimal model order (Table 5), as higher order models do not have acceptable changes in YIC values. The overall relation is seen to be non-linear (Table 5), though less strongly than the overall rainfall–streamflow response. In the case of the overland flow process, this is likely to be due to

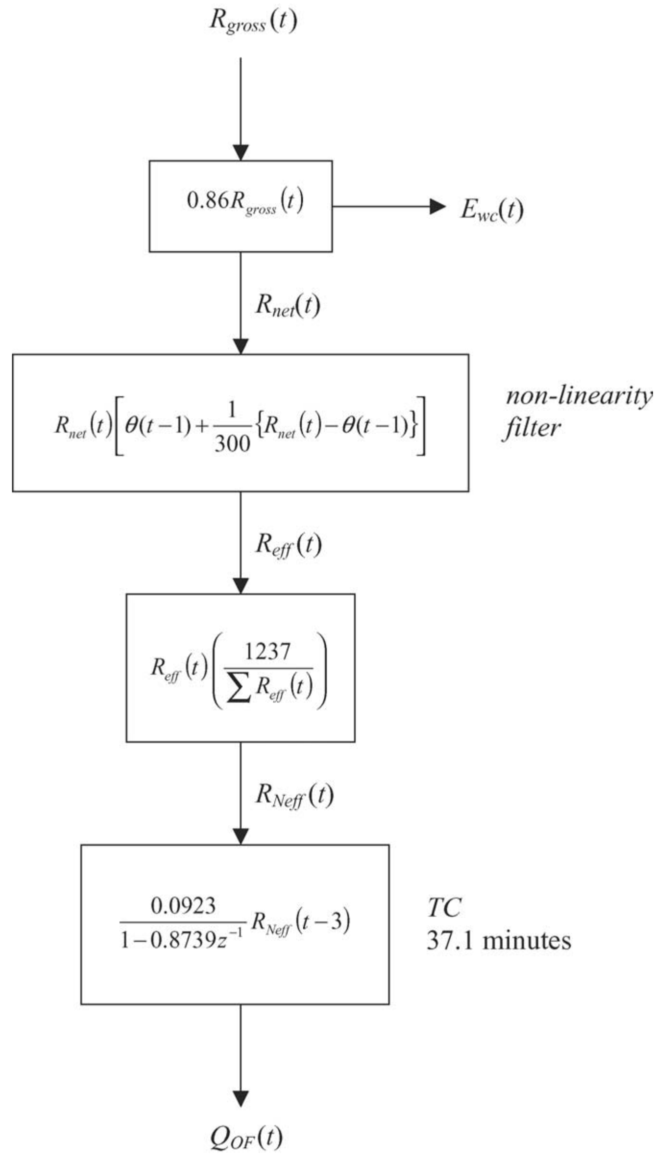

Fig. 5. The first order DBM model of net rainfall to streamflow for the 0.44 km^2 Baru catchment for the 1st July 1995 to 30th June 1996 water year.

the effect of variable near-surface soil-water content. Comparison of the modelled infiltration-excess overland flow time-series for site E4 with that observed is shown for an example rainstorm with a return period of 2 months (ca. 50 mm: Douglas et al., 1999; Bidin, 2001) in Fig. 6, though the whole water year is modelled. The resultant surface flow model and its parameters (based on time-series of 105,408 values) are shown in Fig. 7 and Table 5. It can be seen from the estimate of the time constant of 5.499 ± 0.085 min, that the infiltration-excess overland flow response is much flashier than the streamflow response. This is expected given the limited surface storage and hence less damping of response in comparison to a streamflow response affected by subsurface moisture storage.

4.3. DBM net rainfall–subsurface flow response

Simulation of the subsurface flow was achieved by subtracting the time-series of flows measured at site E4 (i.e.

Table 5
DBM model parameters identified for component water pathways in the third order Baru stream (5°01′N, 117°48.75′E) near the Danum Valley Field Station (Malaysian Borneo)

Parameters and statistics	DBM model				
	1	2	3	4	5
Structure	[1 1 1]	[1 1 1]	[1 1 3]	[1 1 4]	[1 1 0]
R_t^2	0.601	0.732	0.481	0.733	0.794
YIC	−9.578	−9.492	−11.009	−12.124	−8.812
τ	–	385	–	320	–
η	–	1415	–	1176	–
	−0.5224	−0.4028	−0.9681	−0.8685	−0.9060
σ()	0.0049	0.0057	0.0002249	0.0006262	0.0025
P	0.0225	0.0143	0.0263	0.0093	0.00059
$\sigma(P)$	0.0002	0.0001	0.0002	0.0004	<0.00001
TC	7.70	5.499	154.20	35.46	50.7
σ(TC)	0.11	0.085	1.10	0.18	1.40
ssP	0.0472	0.0240	0.8258	0.7088	0.0063
RC*	0.024	0.024	0.709	0.709	–

Model 1: purely linear DBM TF model of net rainfall to overland flow; Model 2: DBM TF with BOSM non-linear model of net rainfall to overland flow; Model 3: purely linear DBM TF model of net rainfall to subsurface flow; Model 4: DBM TF with BOSM non-linear model of net rainfall to subsurface flow; Model 5: purely linear DBM TF model of rising temperature to transpiration. See Table 3 for definition of parameters.

infiltration-excess overland flow) from the streamflow response (i.e. channel-flow measured at site P1 in Fig. 1). The results of the DBM modelling of the net rainfall–subsurface flow relation are shown in Table 5. As with the net rainfall to streamflow model (Table 3), a purely linear model explains only 48.1% of the subsurface flow (Table 5). Similarly, inclusion of the BOSM non-linear filter, here related to unsaturated zone moisture dynamics, increases the level of explanation to 73.3% (Table 5). This first-order model for the subsurface flow response has a pure time delay of four time steps (ca. 20 min) and a time constant (Eq. (3)) of 35.46 ± 0.18 min. As the streamflow is largely derived from subsurface flows, it is not surprising that this value is very similar to the 37.10 ± 0.17 min TC for the net rainfall–streamflow response. Again, such a rapid subsurface pathway probably relates to the absence of a deep aquifer, and hence restriction of flow to shallow soil layers (Chappell et al., 1998, 1999, 2004b) and predominantly convective rainfall regime (Bidin and Chappell, 2006), but also may relate to the presence soil piping within the subsurface system (Chappell et al., 1998; Chappell and Sherlock, 2005). As with the streamflow response, a statistically acceptable higher-order decomposition of the Baru net rainfall–subsurface flow response was not observed.

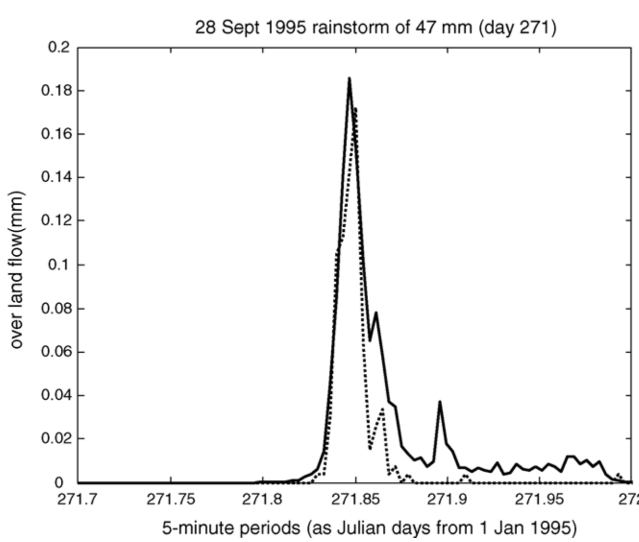

Fig. 6. Infiltration-excess overland flow modelling results for contributory area E4 in the Baru catchment, showing the time-series of the modelled (solid line) and observed (broken line) flow illustrated with an example storm with a 2 month return period (i.e. 28th September 1995), but calibrated to the whole year.

4.4. DBM temperature–local transpiration response

A DBM model explaining much of the variance in transpiration dynamics for individual trees was found after

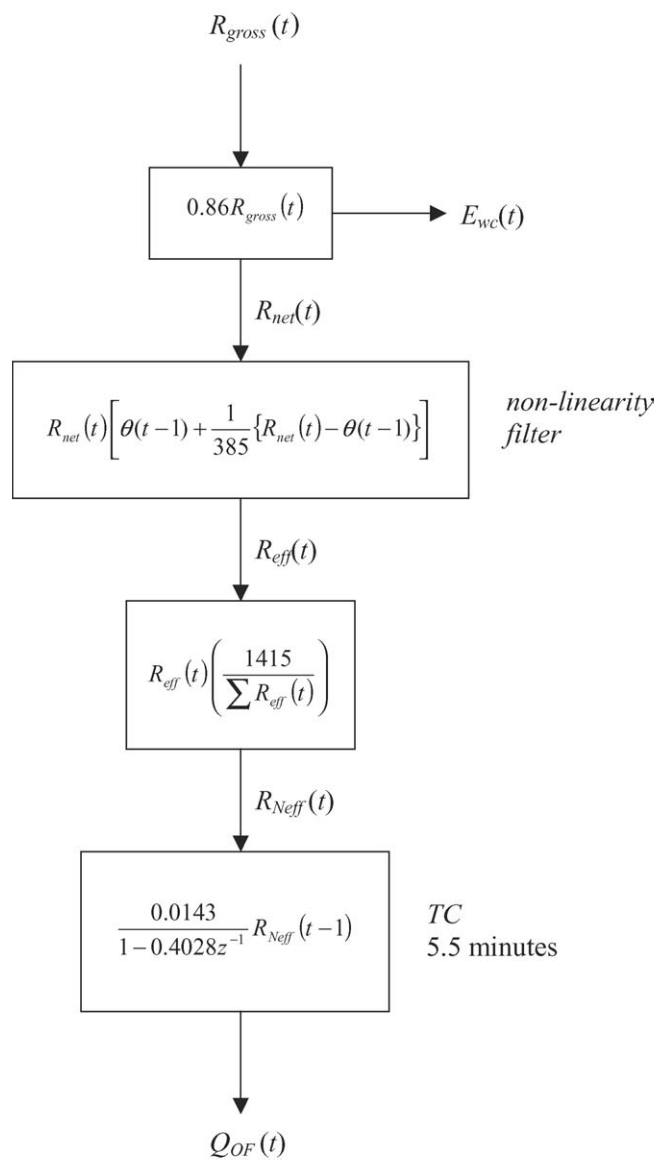

Fig. 7. DBM model of infiltration-excess overland flow for site E4, Baru catchment.

manipulation of air temperature time-series and subsequent transfer function modelling using the SRIV algorithm (Table 4). The existence of this relationship is probably due to both air temperature and transpiration being strongly controlled by the net radiative energy available until midday when the stomata close. For the initial estimate of the catchment-average transpiration presented here, the model for camphor tree K4 scaled to catchment water balance (Eq. (10)) was derived. The temperature time-series associated with this tree was measured at 1 m above ground, 0.5 m away from this tree (shown with a solid line in Fig. 8a). The method we developed first derived observed transpiration rates (mm per 5 min time-step) from the sapflow velocities monitored at tree K4 by multiplying by the sapwood area. These rates were then scaled by the annual proportion of net rainfall generating the streamflow (i.e. 0.23: Eq. (10)), so that the rates are more representative of the catchment-average transpiration. Next the annual minimum temperature was subtracted from the 5 min resolution time-series of air temperature. Readings where temperature had fallen from the previous time-step were then set to zero (mostly the afternoon, when stomata are closed or closing) and the resultant time-series (called $EN(t)$) derived and shown with open circles in Fig. 8a for an example 6-day period. The SRIV algorithm was then used to derive a linear DBM model of the transpiration.

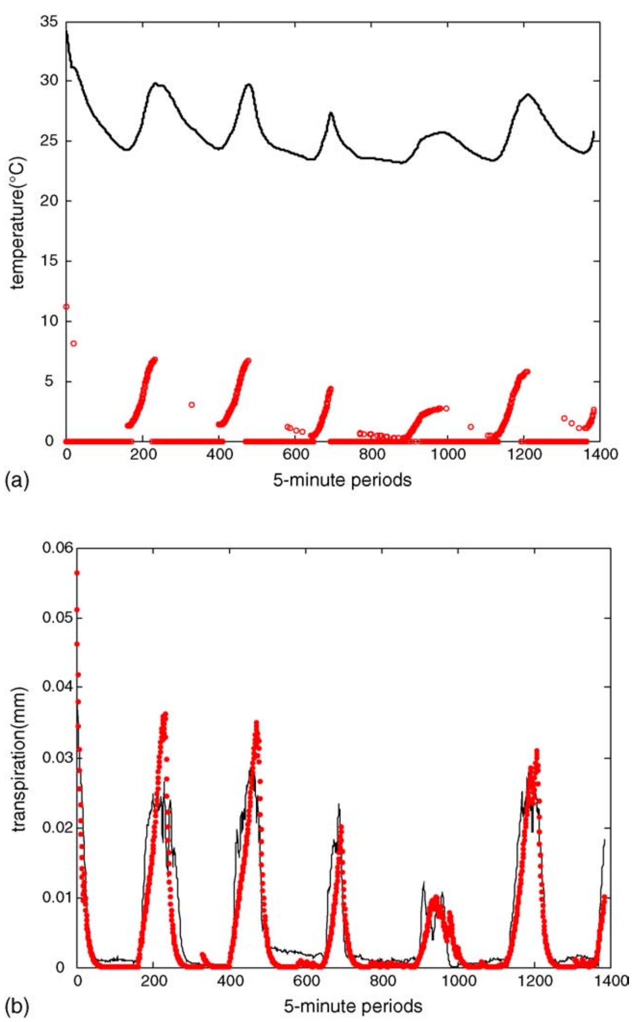

Fig. 8. The model of transpiration from the Baru catchment shown over an example 5-day period in the water year. Subplot: (a) shows the air temperature (solid line) and rising-stage, air temperature (circles) and (b) shows the measured sapflow from camphor (*D. lanceolata*) tree K4 scaled by the Baru water-balance (dotted line) and the modelled transpiration (solid line).

The resultant DBM transfer function model of catchment transpiration has a structure and parameters given as:

$$E_{\mathrm{TRC}}(t) = \frac{0.0010}{1 - 0.9060z^{-1}} EN(t); \tag{15}$$

$$EN(t) = T_{\mathrm{rise}}(t) - T_{\mathrm{min}} \tag{16}$$

where $E_{\mathrm{TRC}}(t)$ is the catchment transpiration at time-step t (mm per 5 min period), and $EN(t)$ is the rising-stage, air temperature at each time-step ($T_{\mathrm{rise}}(t)$) minus the annual minimum air temperature (T_{min}). Both temperature values are in °C. Table 5 shows the model parameters and statistics identified. This linear transfer function model using $EN(t)$ was found to able to explain 79% of the variance in the observed transpiration data (Fig. 8b, Table 5), and helps us understand some of the temporal dynamics of the transpiration processes within rainforest trees of the Baru catchment. First, we can see from the δ-value (Table 5), that there is no time delay between a temperature rise and a change in transpiration rate. Second, a time constant of only 50.7 ± 1.4 min (Table 5) indicates that the transpiration pathway is a very responsive (limited storage) system, when compared to, for example, subsurface pathways in major aquifers (Table 4). We are continuing to evaluate this transpiration model for other trees (with the same and different model parameters) and are looking at the role of the controlling variables of wind speed, saturation deficit of the atmosphere, soil capillary potential and net radiation in DBM simulation of transpiration.

4.5. Linking components for subsequent scenario modelling

Each of the separate DBM models, with their structure and parameters partly derived by the SRIV algorithm, were then combined to give an output comparable to that simulated by the lumped net rainfall to streamflow model and the observed data (Fig. 9). While a streamflow time-series can be constructed by combining the infiltration-excess overland flow and subsurface flow models or simulated results, this second-order behaviour could not be identified from the lumped rainfall–streamflow model because the overland flow component is such a small proportion of the streamflow (i.e. 4.4% of streamflow or 3.2% of net rainfall). Gain elements were then added between the net rainfall and the overland and subsurface flow models (Eqs. (11) and (12)), to allow for changes in the amount of overland flow generated as part of scenario modelling. For simulation of the observed time-series, the gain element of the ϕ_{scenario} parameter (and hence β-parameter) was derived from the observed data (i.e. observed annual proportion of the net rainfall generating overland flow) and thus had no impact on the simulated responses. The ability of the user to manually change this

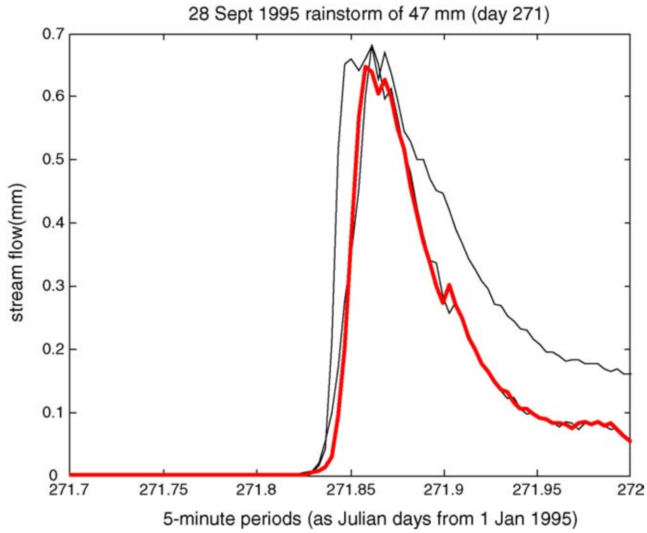

Fig. 9. Observed streamflow in the Baru catchment together with the streamflow estimated by adding the DBM overland flow and DBM subsurface flow models. The model is derived from 12 months data, but illustrated with an example storm with a 2 month return period (i.e. 28th September 1995). The broken line shows the observed streamflow, the solid grey line shows the simulated streamflow estimated by the lumped net rainfall–streamflow model, while the fine solid line is from the combined surface flow (2.4% net rainfall) and subsurface flow model. The simulated streamflow for the combined surface flow (3.2% net rainfall) and subsurface flow model is not shown, but is very similar to the combined model that is shown.

parameter does, however, allow for forestry scenario modelling being undertaken.

The very simple model taking account of the losses due to wet canopy evaporation is effectively a simple gain element with a single parameter α; this is shown in Eq. (8) and Fig. 3. With new data on canopy storage this static model could be developed into a dynamic model. The transpiration model is linked to the other water pathways within the BARUMODEL using an integrator (Fig. 3) that normalises the gain to the annual water-balance. Again, with more data on the controls of transpiration, for example, the effect of canopy wetting on transpiration suppression, a more dynamic linkage with the other BARUMODEL components could be developed.

5. Results: preliminary application to skid trail impacts

Within the first version of the BARUMODEL with its linked DBM-derived components, the surface–subsurface partition (β-value) was changed to simulate two forestry scenarios. Our objective was to focus on the effects of a different density of skidder vehicle trails (or 'skid trails') on the partition between surface and subsurface flow, if other types of forestry practice (i.e. clearfelling or reduced impact logging) had been used instead of conventional selective logging (see Thang, 1987; Thang and Chappell, 2004).

5.1. Appropriate η and ϕ_{obs} values for BARUMODEL

To define appropriate values of η and ϕ_{obs} for BARUMODEL (see Eqs. (7) and (14) and Fig. 3), it is first necessary to review the measured extent of tropical forestry roads and skid trails. Several studies in the wet tropics (e.g. Sinun et al., 1992; Baharuddin, 1995; Douglas et al., 1995; Chappell et al., 1999, 2004a) have shown that localised sections of forest road can generate significantly more infiltration-excess or Hortonian overland flow (HOF) in comparison to adjacent slopes. Similar findings have been obtained for rural roads in the seasonal tropics (Ziegler et al., 2001). The main question is whether localised changes along skid trails associated with tropical forestry have a significant impact on the behaviour of micro-catchment (0.1–1 km^2) areas (Chappell et al., 2004b). Local HOF, because of variation in road orientation and road micro-topography, may run on to side slopes at many locations where it then infiltrates, rather than connect directly to a stream (Sidle et al., 2004; Chappell, personal observations in the Baru catchment, 1990–2004). As a result of these two factors (road orientation and micro-topography), the presence of HOF along short sections of even the most compacted roads might not have a significant impact on stream hydrographs. A noteworthy study undertaken in the north-western USA (Jones and Grant, 1996) does, however, suggest that forest haulage road construction can affect stream hydrographs, notably by increasing storm peakflows. Even with this American study, others (e.g. Thomas and Megahan, 1998) have suggested that the results do no apply to large storms. A major problem for the identification of forest road or skid trail impacts on stream hydrographs in the wet tropics is the lack of high quality streamflow records prior to road/trail construction (Chappell et al., 2004b). This means that modelling possible changes to stream hydrographs resulting from different skid trail scenarios may be useful, at least to help define the scale, duration and local conditions in which to undertake the new field studies required.

The Baru catchment was subject to the first phase of commercial selective logging in 1988/1989 (Table 2). The period of the example analyses (i.e. 1995–1996) is 7-years post-logging activity, so some vegetation recovery on less compacted skid trails will have taken place (Douglas et al., 1995), thus potentially affecting hydrograph shape. Within Malaysian forest reserves, several two-lane, surfaced roads for high speed log transport to the saw mill are constructed-these are called 'primary haulage roads' (Forestry Department Peninsular Malaysia, 1999). These main roads connect to 'secondary haulage roads' that are constructed to serve two or three annual logging coupes. These roads are also surfaced, but normally only have a single lane. Within individual annual logging coupes, un-surfaced 'feeder roads' allow timber lorry access to more distant areas. Within the Baru catchment, we calculate that a total of 1094 m of 'secondary haulage road' was constructed just below the northern divide (Fig. 1), and this had been surfaced with a 0.2 m depth of local chert. A further 719 m of un-surfaced, feeder road was located on the western catchment divide (Fig. 1). The lorries that used these roads, collected the timber from 'log landing areas'.

In most rainforest areas of SE Asia, timber is brought to the log landing areas by cableways (e.g. highlead: Conway, 1982) or skidders, only occasionally are helicopters used. Both of these main primary transportation systems were used within the Baru catchment; the area containing two highlead masts and many skid trails. A recent survey of a 100 m wide corridor along 860 m of the eastern section of the secondary haulage road in the Baru showed 528 m of skidder vehicle trails are present. Thus, for a unit area of the Baru catchment, we calculate that there are 25 m/ha of secondary road, 16 m/ha of feeder road and 61 m/ha of skid trails (Table 6). These forest road/trail surveys show that within the Baru, road/trail densities comply with the Standards of Performance (SOP) required in those 'lowland Dipterocarp forests' that are certified by organisations such as SGS as sustainably managed (Table 1, Thang and Chappell, 2004). The width of the compacted surface of the secondary road in the Baru was found to be approximately 4 m, while the feeder roads and skid trails were approximately 3 m. Thus, the area of the Baru covered by secondary road is approximately 4,376 m^2 or 1.0% of whole catchment, by the feeder road 2,157 m^2 or 0.5%, and by the skid trails 8103 m^2 or 1.8% (if the measured corridor area is representative). Thus, all of the road/trail surfaces occupy only 3.3% of the whole Baru.

To define appropriate values of η and ϕ_{obs} for BARUMODEL (see Eqs. (7) and (14) and Fig. 3), it is secondly necessary to estimate the proportion of infiltration-excess overland flow from different tropical rainforest surfaces. Sinun (1991) and Sinun et al. (1992) reported a mean proportion of infiltration-excess overland flow generated by a mix of disturbed and undisturbed slope sections which lack roads or trails of 2.5% of net rainfall. This figure is similar to the 2.8% of gross rainfall reported by Malmer (1996) on similar soils in managed rainforests in north-western Sabah. At Danum, the highest recorded proportion of infiltration-excess overland flow generated by a skid trail surface was the 52.5% of gross rainfall recorded by Sinun et al. (1992). All of the measurements of Sinun et al. (1992) were undertaken in 1989/1990, shortly after the logging activity in the Baru (Table 2). Most skid trails and un-surfaced feeder roads within the Baru have developed a vegetation cover in the 7-years post logging activity. The feeder road in the Baru is covered by grasses, vines and shrubs, while most skid trails are covered by shrubs and small trees. Douglas et al. (1995) demonstrated that such vegetation re-growth significantly reduces the proportion of HOF generated. In some contrast, the skid trail section that generated the 52.5% HOF remains only sparsely vegetated due in part to the very high degree of compaction (see, Nussbaum et al., 1995). Thus, the 52.5% HOF may be considered representative of some sections of well-used feeder roads and skid trails, but not representative of most skid trails in the Baru, with their lower levels of compaction. Indeed, some skid trail sections in the Baru (e.g. site E4 in Fig. 1) generated only 2.4% of net rainfall as HOF some 7-years post logging (Chappell et al., 1999). Critically, even where skid trails or roads generate local HOF, a significant quantity is seen to run-off onto side slopes where it then infiltrates rather than directly enter the stream channels (Chappell, personal observations in the Baru catchment, 1994–2004). As a consequence of these two factors, reducing the observed proportion of HOF along skid trails from the measured highest 52.5% value (on a very compacted surface) to say 20% would not be unrealistic for a typical road/trial surface. Overland flow was not visible on the secondary haulage road in the Baru, except where streamflow from an upslope channel discharged onto the road during storms (e.g. site E2 in Fig. 1). The high infiltration capacity of the coarse chert surface of the haulage road allows rainfall to infiltrate. Some of this water may: (a) percolate in an upslope direction to supply the road drain (a proportion of which then inputs directly to a stream channel), but the remaining proportion probably (b) percolates into the downslope soils. Thus, the 20% HOF value for the skid trails is not unrealistic for the secondary roads also.

If these very approximate estimates from the three road/trail surfaces are combined with the figure for the other slopes, then a value for the HOF proportion for the whole Baru catchment would become:

$$(0.04\,\text{fractional area} \times 20\%) + (0.96\,\text{fractional area} \times 2.5\%) = 3.2\%\,\text{of net rainfall} \quad (17)$$

Table 6
Density of haulage roads, feeder roads and skid trails within selected catchments, together with the maximum values currently allowed in certified forests in Peninsular Malaysia

Site	Logging operation	Density (m/ha)			
		Haulage road	Feeder road	Skid trail	Total
Actual road and trail densities in selected Malaysian rainforests					
(1) Baru	Selective	25	16	61*	102
(2) Bukit Berembun	Selective (CONV)	0	56	69	125
(3) Bukit Berembun	Selective (RIL)	0	60	22	82
(4) Bukit Tarek (C3)	Clearfelling	0	52	176	228
Current maximum allowable road and trail densities (standards of performance)					
(5) Peninsular Malaysia	Selective	–	<40	<300	–
(6) Sabah	Selective	–	<20	–	–

Notes: (1) From Chappell (unpublished); (2) and (3) derived from a map in Abdul Rahim (1990) for conventional selective logging (CONV) and for closely supervised logging, also called reduced impact logging (RIL); (4) from Noguchi et al. (2004); (5) and (6) see Thang and Chappell (2004) for lowland Dipterocarp forest. (*) From a survey of skid trails within an 860 m long and 100 m wide corridor centred on the secondary haulage road (given the proximity to the road, this possibly an over-estimate for the catchment as a whole).

Even if the highest measured HOF value (i.e. 52.5%) was used to represent all road and trail surfaces, this would still only give a value of 4.5% HOF for the Baru as a whole.

As a result of these analyses of road/trail contributions to overland flow in the Baru catchment, the observed proportion of net rainfall that becomes infiltration-excess overland flow (i.e. 0.024 at site E4), we scale to 3.2% of net rainfall. The result of this scaling has only a relatively small impact on the model parameters (Table 7) or hydrograph form. Fig. 9 shows the observed streamflow for the example storm with a return period of 2 months with the time-series constructed by combining the 3.2% infiltration-excess overland flow and associated subsurface flow modelling results. For the whole 12-month period, the combined model with 3.2% overland flow explains 76.67% of the variance in the observed streamflow, which is only slightly less than the combined model with 2.4% overland flow (76.99%) or the lumped net rainfall–streamflow model with 77.43% of variance explained (Table 3). Thus, the combined surface–subsurface models would be only slightly less accurate for forecasting streamflow in comparison to the lumped model, but they have the advantage that the effects of modifying the surface–subsurface partition can be readily undertaken and seen.

5.2. Appropriate $\phi_{scenario}$ and β-values for forestry skid trail scenarios

The density of skid trails within the Baru catchment is comparable to that in the Bukit Berembun C1 catchment (Peninsular Malaysia) with its similar conventional selective logging practices (Table 6). The Baru skid trail density is, however, a factor of 2.8 larger than that of the reduced impact logging (RIL) site at Bukit Berembun and a factor of 2.9 fold smaller than that in the clearfelled Bukit Tarek catchment also in Peninsular Malaysia (Abdul Rahim, 1990; Noguchi et al., 2004; Table 6). Given this finding, two possible forestry management 'scenarios' might be:

(1) What is the impact of a skid trail density comparable to Malaysian RIL forestry on the Baru stream hydrograph (following 7-years of recovery)?
(2) What is the impact of a skid trail density comparable to Malaysian clearfell forestry on the Baru stream hydrograph (following 7-years of recovery)?

If the statistical distribution of infiltration capacity of the skid trails under RIL or clearfell operations is assumed to be similar to that under the conventional selective logging undertaken in the Baru during 1988/89, then the proportion of infiltration-excess overland flow within the Baru can be changed by simply altering the ϕ_{scenario} term, and hence β-term (see Eq. (14)) in the gain elements for the overland and subsurface flow partition. In both scenarios, ϕ_{scenario} was changed to reflect the altered density of skid trails. If the number of skid trails seen within a Malaysian RIL system had been present within the Baru, but with the same soil characteristics ('scenario 1'), then the fractional area covered by skid trails would reduce to 0.0143 (i.e. 0.04/2.8), so that the proportion of net rainfall as overland flow (ϕ_{scenario}) over all types of slope in the catchment would reduce to:

$$\begin{aligned}&(0.014\,\text{fractional area} \times 20\%)\\&\quad + (0.986\,\text{fractional area} \times 2.5\%)\\&\quad = 2.75\%\,\text{of net rainfall}\end{aligned} \tag{18}$$

In some contrast, if the number of skid trails seen within a Malaysian clearfell system had been present within the Baru, but with the same soil characteristics ('scenario 2'), then the

Table 7
DBM model parameters identified for the Baru stream (5°01′N, 117°48.75′E) near the Danum Valley Field Station (Malaysian Borneo), after (a) weighting the infiltration-excess according to road and skid trails areas, (b) undertaking a scenario with the density of skid trails seen with Malaysian reduced impact logging, and with (c) Malaysian clearfell forestry

Parameters & statistics	DBM model					
	1a	1b	2a	2b	3a	3b
Structure	[1 1 1]	[1 1 4]	[1 1 1]	[1 1 4]	[1 1 1]	[1 1 4]
R_t^2	0.7322	0.715	0.732	0.726	0.732	0.678
YIC	−9.492	−11.948	−9.492	−12.054	−9.492	−11.637
τ	385	320	385	320	385	320
η	1415	1150	1415	1169	1415	1132
	−0.4028	−0.8739	−0.4028	−0.8709	−0.4028	−0.8828
$\sigma()$	0.0057	0.0006	0.0057	0.0006	0.0057	0.0007
P	0.0191	0.0884	0.0164	0.0910	0.0271	0.0806
$\sigma(P)$	0.0002	0.0004	0.0001	0.0004	0.0002	0.0004
TC	5.499	37.10	5.499	36.180	5.499	40.10
σ(TC)	0.085	0.199	0.085	0.188	0.085	0.24
ssP	0.0320	0.7009	0.0275	0.7051	0.0453	0.6871
RC*	0.0320	0.7006	0.0275	0.7051	0.0453	0.6873

Model 1a: DBM TF with BOSM non-linear model of net rainfall to 3.2% overland flow; Model 1b: DBM TF with BOSM non-linear model of net rainfall to subsurface flow when overland flow is 3.2%; Model 2a: DBM TF with BOSM non-linear model of net rainfall to overland flow given RIL skid trails; Model 2b: DBM TF with BOSM non-linear model of net rainfall to subsurface flow when overland flow is 2.75% (RIL); Model 3a: DBM TF with BOSM non-linear model of net rainfall to overland flow for clearfell skid trails; Model 3b: DBM TF with BOSM non-linear model of net rainfall to subsurface flow when overland flow is 4.53% (clearfell). See Table 3 for definition of parameters.

area covered by skid trails would increase to 0.116 (i.e. 0.04×2.9), so that the proportion of net rainfall as overland flow (ϕ_{scenario}) over all types of slope in the catchment would increase to:

$$\begin{aligned}&(0.116\,\text{fractional area} \times 20\%)\\ &\quad + (0.884\,\text{fractional area} \times 2.5\%)\\ &\quad = 4.53\%\ \text{of net rainfall} \qquad (19)\end{aligned}$$

The resultant β-values for the RIL and clearfell scenarios would be 0.859 (i.e. 2.75/3.2) and 1.416 (i.e. 4.53/3.2), respectively. For these examples, only the effect of skid trail density on the amount of net rainfall following a purely surface pathway or purely subsurface pathway was simulated directly. Clearly, a greater coverage of skid trails is likely to be associated with greater canopy damage, so the rates of both wet-canopy evaporation and transpiration would be different also (Bidin, 2001; Chappell et al., 2001; Bidin et al., 2003). In the two scenarios presented here, wet-canopy evaporation and transpiration remain unchanged after altering the surface–subsurface partition. Following future improvements to the BARUMODEL evapo-transpiration components, we then aim to examine the direct and indirect effects of forestry operations on the wet-canopy evaporation and transpiration.

5.3. Results of the skid trail scenario modelling

The predicted streamflow results for 'scenario 1: skid trail density in a RIL system' are illustrated in Fig. 10, while those of 'scenario 2: skid trail density in a clearfell system' are illustrated in Fig. 11. The scenario modelling was undertaken for the 12-month period comprising of 105,408 values in each time-series, but the effects are illustrated by plotting the hydrograph of a storm with a return period of 2 months, i.e. ca. 50 mm/day (see Douglas et al., 1999; Bidin, 2001). Figs. 10a and 11a show the impact on the infiltration-excess overland flow component during the example storm with a 2-month return period (28 September 1995) while Figs. 10b and 11b show the overall impact on the streamflow during the same example storm. With the Malaysian RIL scenario where the overall overland flow proportion is reduced from 3.2 to 2.75% of net rainfall, the overland flow in the ca. 50 mm event reduced by 16.38%. In contrast, under the Malaysian clearfell scenario where the overall overland flow proportion is increased from 3.2 to 4.53% of net rainfall, the overland flow for the same event increased by 29.34%. Critically, the streamflow peak of the same event actually increased marginally by 0.65% during the RIL simulation, and reduced again marginally by 1.66% during the clearfell simulation. These results are representative of the changes seen within the other storms that comprise the 12-month record. The perhaps unexpected result of a reducing stream peakflow, although the small change is well within the uncertainty of both the time-series data and modelling, arises because the contribution of the overland flow is on the rising stage, not the peak of the stream hydrograph (see Fig. 11b). Thus, slightly more water moves along the overland flow pathway at the start of the storm, leaving slightly less for the subsurface pathway which makes up the majority of the streamflow peak. The opposite result is seen with the RIL scenario.

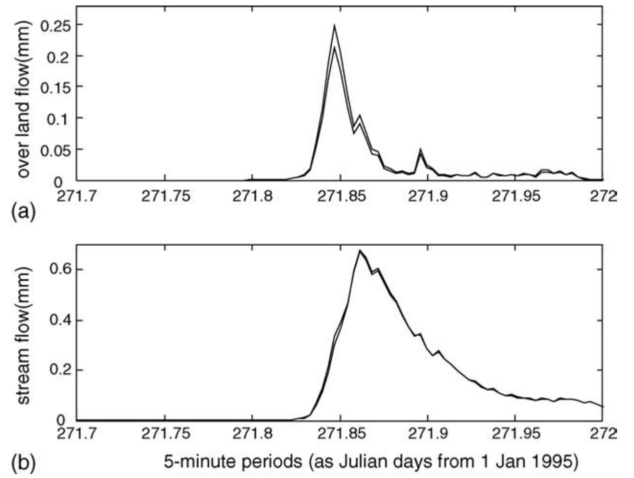

Fig. 10. Simulated streamflow for the Baru catchment for the example storm with a return period of 2 months (broken line) together with that predicted using the density of skid trails from the reduced impact logging (RIL) system of Bukit Berembun (solid line).

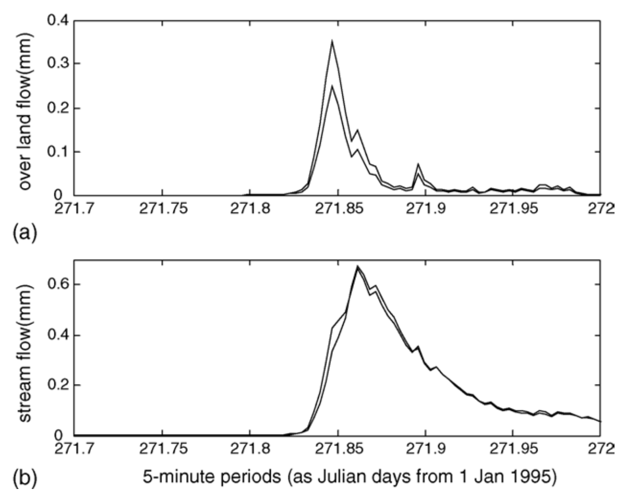

Fig. 11. Simulated streamflow for the Baru catchment for the example storm with a return period of 2 months (broken line) together with that predicted using the density of skid trails from the clearfell system of Bukit Tarek (solid line).

6. Discussion

The aim of this study was to identify water pathways within a humid tropical catchment using Data Based Mechanistic (DBM) modelling, and then to apply the resultant models to predict the effects of skid trail density within differing rainforest management systems on the streamflow hydrograph. A key underlying objective was to demonstrate the value of further analysis of existing high quality time-series hydrological data from tropical rainforest catchments. A linkage of the component DBM models into a single structure for the assessment of conceptual or data limitations and for subsequent scenario simulation we call the BARUMODEL. The model should be considered to have a form which requires development, but has already allowed us to newly consider differences between water pathways, where new process monitoring is required, and how we might devise new experiments to evaluate forestry impacts within our equatorial rainforest catchment. All of these issues have been aided by the fact that the DBM-defined components of BARUMODEL are clearly visible and can be readily modified as new time-series data sets become available. This is a clear advantage of a model based on observed time-series components over many physics-based catchment models.

6.1. Hydrological interpretation of DBM model structures and parameters

Even after more than 30 years of research into water pathways within the wet tropics, there remains much debate about: (a) the magnitude of infiltration-excess overland flow; (b) the dominant pathway of water in the subsurface; and (c) the best way of examining the controls on the runoff pathways (see e.g. Bonell, 2004; Chappell et al., 1998, 2004b; McDonnell, 2003; Chappell, 2005; Chappell and Sherlock, 2005). Thinking about tropical water pathways inferred from DBM modelling has not been widely undertaken and, therefore, more DBM modelling has the potential to add to the debate about the tropical flow processes and their assessment. DBM models can: (a) show differences in the non-linearity of water pathways; (b) show whether distinctly different water pathways express themselves in the streamflow records; (c) show differences in the flashiness or residence times of catchments or individual water pathways; (d) show relationships between variables not previously considered locally; and (e) provide a robust basis for forecasting future streamflow values.

Within this study, DBM modelling has shown that the streamflow generation model is very poor when only linear dynamics are considered, with a 28 percentage point increase in variance explained where the BOSM non-linear filter is added (Table 3). The strong non-linearity in the response relates to the dominant subsurface pathway, specifically to the dynamic effects of unsaturated zone storage (Young and Beven, 1994) or the vertical distribution of permeability in the phreatic zone (Kirkby, 1975; Chappell et al., 2004c). This contrasts with the infiltration-excess overland flow response, which has a much smaller 13 percentage point increase in variance explained where the BOSM non-linear filter is added (Table 5). Thus, the non-linearity in the infiltration-excess overland flow response due to variations in ground-surface wetness (Horton, 1933), exerts a much smaller influence on infiltration than do the water content dynamics in the whole soil-rock profile on subsurface drainage and exfiltration.

Some conceptual models, even those which are said to be data-based (e.g. Croke et al., 2004), can assume the effects of two distinct water pathways express themselves in the streamflow response, and so use a model structure with two pathways. The DBM modelling with its ability to use SRIV to search for higher order models, indicates that no more than one very dominant pathway has expression in the Baru stream hydrograph. This does not mean that two or indeed many more surface and subsurface pathways are absent with the catchment, just that: (i) one pathway totally dominates the response; (ii) the combined effect of several pathways has the appearance of a first order response; or (iii) the DRCs, notably δ and TC, of the component pathways are not sufficiently different. Many catchments where DBM modelling identifies a second order model have a marked seasonality in a deep aquifer response combined with a very flashy storm-related response in the shallow subsurface. If the subsurface system does not express such a higher order response in the streamflow records, but we a priori assume a second order model, then uncertainty in our DRCs or parameters increases, sometimes dramatically (Young, 1992).

We expect that the infiltration-excess overland flow pathway responds more quickly and for a shorter time than the subsurface response which dominates the stream hydrograph. This DBM study quantifies the difference in these dynamic response characteristics using models derived from observed time-series, possibly for the first time in a humid tropical forest, and certainly for DBM modelling. The infiltration-excess overland flow pathway has a shorter pure time delay before initial response of 1 time-step (ca. 5 min: Table 5) compared to the streamflow response which is 3 time-steps (ca. 15 min: Table 3). Similarly this path recesses faster with a TC of 5.5 min (Table 5) versus the very different 37 min of the overall streamflow response (Table 3). The limited number of DBM studies of runoff processes presented in Table 4 highlights the need to undertake further DBM modelling work in the wet tropical forests having a wide range of climatic and terrain conditions. The more time-series that are modelled, the greater the degree of interpretation of the DRCs that can be made. The derivation of a subsurface flow time-series from a combination of the streamflow and infiltration-excess overland flow time-series is acceptable as a first approximation, given that the streamflow is 96% subsurface flow. The need for this approximation does, however, highlight the need to obtain independent time-series of subsurface flow for subsequent DBM modelling, perhaps from continuous tracer releases, throughflow troughs or borehole data. We are, however, aware of the current limitation of these three techniques in deriving subsurface flow time-series (Knapp, 1970; Fawcett et al., 1997; Chappell and Sherlock, 2005). While we know that the infiltration-excess overland flow pathway responds faster than the subsurface path with its longer route and greater storage, having a simulation model derived directly from tropical observations should be helpful for future research on tropical runoff processes.

The DBM model of rising air temperature to transpiration shows that there is a strong, dynamic relationship between these two variables at least within the selected rainforest trees. Air temperature is a commonly measured meteorological variable in rainforest sites, so the model shows the potential for future studies that might generate transpiration models from even short runs of transpiration data. The transpiration is probably not responding to air temperature, but to those meteorological variables (e.g. net radiation) that also affect air temperature. We, therefore, intend to extend our DBM modelling of transpiration by looking at its relationship with a range of hydro-meteorological variables, notably wind speed, saturation deficit of the atmosphere, soil capillary potential and net radiation (see Roberts, 2000). We also intend to extend the DBM modelling of transpiration to sapflow data-series collected from other tree species in the wet tropics (see e.g. Eschenbach et al., 1998) and other transpiration measurement methods, e.g. eddy covariance (see e.g. Kumagai et al., 2004). A Global Atmospheric Watch (GAW) tower was recently constructed on a hill 2 km to the east of the Baru catchment. We plan to undertake such measurements on this 100 m GAW tower. Critically, this tower has the potential to allow us to measure catchment-lumped estimates of transpiration, rather than trying to capture spatial variability with many tree-scale measurements. Further DBM modelling of transpiration would then allow greater hydro-meteorological interpretation of the DRCs which comprise the DBM transpiration models. Equally, our planned instrumentation of the Baru canopy with wetness sensors (i.e. 237 Wetness Sensing Grids from Campbell Scientific Ltd., Shepshed, UK), may help us understand transpiration suppression during storms, but also allow us to develop a dynamic DBM model of wet canopy evaporation. Wet canopy evaporation was poorly parameterised as a long-term average value in this study (i.e. $1 - \alpha$, see Eq. (8) and Fig. 3). Improved parameterisation of the evapo-transpiration components should allow more complete scenarios of the tropical forestry impacts including canopy and terrain changes to be assessed.

6.2. BARUMODEL application to runoff impacts of skid trail density

The BARUMODEL simulations indicated that while the overland flow pathway reduced with Malaysian RIL and increased with Malaysian clearfell systems during all storms studied, this did not increase the stream hydrograph peaks because most overland flow contributed before the peaks. The fact that our scenario modelling indicates that stream peak flow does not change significantly with a greater or lesser proportion of overland flow also results from its relatively insignificant contribution to the overall streamflow at our equatorial rainforest site. This result, which goes against the popular perception of the impacts of tropical forest skid trails on stream flashiness (see Chappell, 2005) is, however, consistent with our modelling of rainfall-runoff data for the Bukit Berembun catchments in Peninsular Malaysia, just before and just after forestry operations (Chappell et al., 2004b). In the case of the BARUMODEL simulations presented here, it must be remembered that the time-series data collected and analysed were from a period 7-years post the initial phase of selective logging. As a result, the overland flow behaviour monitored may be volumetrically less significant than would have been the case during the logging operations or immediately after (Douglas et al., 1995). It should be remembered, however, that the clearfell scenario assumed that overland flow on skid trails and roads amounted to 20% of net rainfall, which is still are large proportion even for the logging period (see Sinun et al., 1992). Further, we would expect that the less vegetated nature of skid trails during the logging period would give greater overland flow volumes, and thus a quicker response. Hence it is not expected that the peak in the overland flow becomes more synchronous with the streamflow peak thereby giving a significant impact, if anything, they would become further apart.

With the two forestry scenarios illustrated here, we can see that the streamflow hydrograph is dominated by waterflows in non-road/trail parts of the catchment (see Eq. (17). We would suggest that new quantitative data on surface water-flows (see Chappell et al., 2004a), subsurface flows and properties such as the soil infiltration capacity and permeability distribution (see Chappell et al., 1998) from non-road or non-trail parts of the Baru catchment are required urgently in this and other rainforest catchments to better understand differences between different tropical forestry systems.

The first episode of selective felling of tropical rainforests has physical impacts resulting from changes to: (a) the forest canopy; and (b) the terrain (Chappell et al., 2004b). Thus far, we have only addressed the impacts of skid trails on the terrain and not the canopy. Clearly, if the wet-canopy evaporation and transpiration components in the BARUMODEL can be better modelled, then changes to these pathways could be assessed.

While the scenario modelling indicates that the streamflow peak is unaffected by different densities of skid trails typical of different Malaysian logging systems, altering the proportion of overland flow on disturbed surfaces, even by only a few percent may have a very significant impact on the sediment delivery (Douglas et al., 1992, 1999). Indeed, reviews by Bruijnzeel (1990, 2001) and Chappell et al. (2004b) show that the greatest physical impact of tropical forestry is on sediment yield. We, therefore, need and intend to extend the BARUMODEL approach to time-series sediment flux data from the nested contributory areas in the Baru and thereby extend the sediment analysis of Chappell et al. (1999, 2004a). Again, one of the objectives would be to develop a model where the effect of changing the relative contributions from different monitored sources (e.g. landslides, culvert collapses, surface wash areas on roads: see Chappell et al., 2004a) to the whole catchment sediment yield can be assessed. This would allow a potentially more significant forestry impact to be quantified and thereby used by other to improve sustainable forestry guidelines for equatorial rainforests.

7. Conclusions

The exercise of identifying DBM model structures and DRCs from multiple water pathways in the same equatorial forest catchment, and their combination to make a preliminary assessment of varying skid trail density effects on runoff response, yields six conclusions:

1. The relationship between equatorial rainfall and overland flow or temperature and transpiration, sampled every 10 s and integrated to a 5 min time-series, can be modelled using a Single-Input-Single-Output (SISO) DBM approach. The rainfall-HOF and temperature–transpiration models may be the first such DBM models for equatorial rainforests.

This success allows the characteristics (DRCs) of these water pathways to be compared with those of the lumped rainfall–streamflow DBM model, and the potential for building a multi-component catchment model where some components have small impact on streamflow prior to any disturbance.

2. Process hydrologists and forest hydrologists expect the infiltration-excess overland flow pathway to be related to rainfall in a more linear manner, respond more quickly and for a shorter time than the subsurface response which dominates the stream hydrograph. This study for the first time quantifies these three characteristics (i.e. τ, δ, TC) for overland flow in a wet equatorial rainforest, allowing objective comparison with the lumped streamflow response or a derived subsurface flow response (i.e. $Q(t)$-$Q_{\mathrm{QF}}(t)$). Thus, for the representative slope section generating infiltration-excess overland flow, the three characteristics are: 385, 1 and 5.5 for τ, δ and TC, respectively, while for the response of the 0.44 km^2 Baru catchment stream they are: 300, 3 and 37. These are considered to be relatively reliable estimates of these hydrological DRCs. This reliability uniquely comes from calibration of model structure and parameters using the SRIV algorithm and because only those component DBM models that have pathways having expression in an output time-series, are considered statistically acceptable.
3. A new, but explicitly preliminary, DBM model of transpiration shows that a Transfer Function with only rising air temperature as the input explains 79% of the variance in transpiration from individual rainforest trees. Thus far, only 15-year-old camphor (*D. lanceolata*) trees have been monitored and modelled. The preliminary estimate of catchment-wide transpiration was made by using an integrator which normalises the data for a representative tree response using the difference in the annual average net rainfall and streamflow.
4. Modelling the streamflow generation pathways, by separate DBM modelling of the component pathways rather than DBM identification of only the dominant pathways expressed in the streamflow records, gives a slightly less accurate streamflow model, but one which allows volumetrically insignificant component pathways to be studied and altered. Our field data in the Baru catchment showed that the infiltration-excess overland flow pathway contributed only a very minor component of the streamflow hydrograph. The representative overland flow site carried only 2.4% of the net rainfall. Preliminary analysis of water balances for all overland flow sites combined with an analysis of haulage road and skid trail density in the Baru suggested that a figure of 3.2% of net rainfall would be more representative. Thus, the catchment model made by combining the DBM model of overland flow with the DBM model of subsurface flow, normalised the partition between long-term overland flow and subsurface flow to 3.2 and 71.6%, respectively. Gain elements using β and $1-\beta$, were then added to allow this partition to be altered to simulate the effects of a different proportion of slid trail surface with its representative value of overland flow. These gain elements, combined with the linked DBM overland flow and DBM subsurface flow models and the DBM transpiration model, linked with an integrator, we call the BARUMODEL.
5. Reviewing published figures of skid trail density within Malaysian rainforests affected by forestry, suggests the Reduced Impact (RIL) forms of selective logging have a factor of 2.8 fewer skid trails, while clearfell forms of logging have a factor of 2.9 more skid trails. Weighting the overland flow according to these different areas, but assuming the same dynamics for a unit area of skid trail, this gives 2.75 and 4.53% of net rainfall moving as overland flow, respectively. Within BARUMODEL, the subsurface flow is changed proportionately (i.e. $1-\alpha$) to reflect the changed overland flow, thus the simulated annual streamflow total remains unchanged. The time distribution of streamflow does, however, change. The most obvious change is to the rising stage of hydrographs during larger rainstorms, e.g. those with a return period of 2 months or ca. 50 mm/day. Selecting one such storm for illustration, the simulation showed that the peak overland flow reduced by 16% for the Malaysian RIL system, and increased by 29% for the Malaysian clearfell system. Critically, the simulated streamflow peak marginally increased with RIL and marginally decreased with clearfelling, though both changes are within the data and modelling uncertainty. This arose because the overland flow contributes primarily to the rising stage, rather than peak of each stream hydrograph. The insignificant impact of overland flow on skid trails to the streamflow hydrograph is consistent with our review and modelling work elsewhere in Malaysia and the humid tropics and supports the idea that the popular perception of the impacts of tropical forestry on hydrology can be exaggerated in some cases. This does not mean that even very small changes to the overland flow pathway are not important. Erosion and sediment delivery are very sensitive to even small changes in overland flow within disturbed rainforest areas (Douglas et al., 1995, 1999). This observation suggests that we should extend our DBM-based scenario modelling to sediment delivery in the Baru catchment where we have time-series data representative of the dynamics of different sediment sources.
6. Assessing and combining the different water pathway components within the BARUMODEL has highlighted several significant limitations of our existing data and hence modelling capabilities. We need high frequency (e.g. a 5 min time-base) sampling of wet canopy evaporation by measuring canopy wetness in addition to the gross and net rainfall. Transpiration dynamics more representative of catchment-wide behaviour would come from: (a) sapflow measurements on many different tree genera; (b) use of other meteorological input variables; and (c) using eddy covariance measurements from the 100 m tower by the Baru catchment in particular. Many more measurements of infiltration-excess overland flow, particularly in the more extensive non-road or non-trail areas when combined with DBM modelling of all sites (see Fig. 1), would improve the reliability of the catchment-average DBM model of this surface pathway. We continue to

search for time-series of subsurface flow that would be a better representation of the below ground pathway rather than the $Q(t) - Q_{OF}(t)$ time-series used here. Developing a dynamic partition between overland flow and subsurface flow variables rather than the static (long-term) partition used here would also improve the statistical and physical robustness of the BARUMODEL. Similarly the effect of rainfall on transpiration, namely transpiration suppression during rainstorms, will be simulated as canopy wetness and new sapflow data become available, thus improving the BARUMODEL linkages. All of these issues highlight the need for much more time-series data collection within wet equatorial rainforests managed for timber production. The DBM modelling should be considered a method to identify dynamic linkages between hydrological variables and data limitations and thus areas for new research, rather than a conclusion to field research.

Acknowledgements

In particular, the authors wish to acknowledge the considerable efforts of Mohamed Jamal Hanapi, Johnny Larenus and Paun Kukuon who have had the primary responsibility for the field data collection in the Baru catchment over the last 10 years. The considerable support of Yayasan Sabah (Forestry Division and R&D Division) and the Danum Valley Management Committee has been invaluable to all aspects of our work. Others making a significant contribution to the success of this particular study are the Royal Society of London (South East Asia Rainforest Research Programme) and the Danum Survey Team (Ismail Abdul Samat, Shaidih Abdul Samat and Nick Chappell). Comments from Prof Keith Beven (Lancaster University), issue co-editor (Prof Tani, Kyoto University) and manuscript reviewers are gratefully acknowledged. Discussions on various aspects of this work with participants at the IUFRO Forest Hydrology workshop in Kota Kinabalu, Sabah, 10–15th July 2004 was most valuable and thus much appreciated.

References

Abdul Rahim, N., 1990. The effects of selective logging methods on hydrological parameters in Peninsular Malaysia. PhD Thesis, University of Wales, Bangor, unpublished.

Baharuddin, K., 1995. Effects of properties and soil erosion in a hill dipterocarp forest of Peninsular Malaysia. Research Pamphlet No. 119. Forestry Research Institute of Malaysia, Kuala Lumpur.

Bathurst, J.C., Ewen, J., Parkin, G., O'Connell, P.E., Cooper, J.D., 2004. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. J. Hydrol. 287, 74–94.

Beven, K.J., 2000. Uniqueness of place and process representations in hydrological modelling. Hydrol. Earth Syst. Sci. 4, 203–214.

Beven, K., 2001a. On fire and rain (or predicting the effects of change). Hydrol. Process. 15, 1397–1399.

Beven, K., 2001b. How far can we go in distributed hydrological modelling? Hydrol. Earth Syst. Sci. 5, 1–12.

Beven, K.J., 2002. Towards an alternative blueprint for a physically-based digitally simulated hydrologic response modelling system. Hydrol. Process. 16, 189–206.

Beven, K., Freer, J., 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. J. Hydrol. 249, 11–29.

Bidin, K., 2001. Spatio-temporal variability in rainfall and wet-canopy evaporation within a small catchment recovering from selective tropical forestry. PhD Thesis. University of Lancaster, Lancaster (UK), unpublished.

Bidin, K., Chappell, N.A., 2003. First evidence of a structured and dynamic spatial pattern of rainfall within a small humid tropical catchment. Hydrol. Earth Syst. Sci. 7, 245–253.

Bidin, K., Chappell, N.A., 2006. Characteristics of rain-events at an inland locality in Northeastern Borneo. Hydrol. Process., in press.

Bidin, K., Chappell, N.A., Sinun, W., Tangki, H., 2003. Net-rainfall and wet-canopy evaporation in a small selectively-logged rainforest catchment, Sabah, Malaysia. In: Proceedings of First International Conference on Hydrology and Water Resources in Asia Pacific Region, vol. 2, pp. 659–666.

Bonell, M., 2004. Runoff generation in tropical forests. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 314–406.

Box, G.E.P., Jenkins, G.M., 1970. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco.

Bruijnzeel, L.A., 1990. Hydrology of Moist Tropical Forest and Effects of Conversion: A State of the Art Review. UNESCO, Paris.

Bruijnzeel, L.A., 1992. Managing tropical forest watersheds for production: where contradictory theory and practice co-exist. In: Miller, F.R., Adam, K.L. (Eds.), Wise Management of Tropical Forests, Proceedings of the Oxford Conference on Tropical Forests, 1992. Oxford Forestry Institute (University of Oxford), Oxford, pp. 37–75.

Bruijnzeel, L.A., 2001. Forest hydrology. In: Evans, J. (Ed.), The Forests Handbook. Blackwell, Oxford, pp. 301–343.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104, 185–228.

Camarasa, A.M., Tilford, K.A., 2002. Rainfall-runoff modelling of ephemeral streams in the Valencia region (eastern Spain). Hydrol. Process. 16, 3329–3344.

Chappell, N.A., 2005. Water pathways in humid forests: myths vs. observations. Suiri Kagaku (Water Sci.) 48, 32–46.

Chappell, N.A., Fowell, M., 2003. Evaluation of GCM simulation of humid tropical hydrology. UGAMP Newslett. 27, 8–9.

Chappell, N.A., Sherlock, M.D., 2005. Contrasting flow pathways within tropical forest slopes of Ultisol soil. Earth Surf. Process. Landforms 30, 735–753.

Chappell, N.A., Ternan, J.L., 1992. Flow-path dimensionality and hydrologic modelling. Hydrol. Process. 6, 327–345.

Chappell, N.A., Franks, S.W., Larenus, J., 1998. Multi-scale permeability estimation for a tropical catchment. Hydrol. Process. 12, 1507–1523.

Chappell, N.A., McKenna, P., Bidin, K., Douglas, I., Walsh, R.P.D., 1999. Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. Philos. Trans. Royal Soc. Lond. Ser. B. 354, 1831–1846.

Chappell, N.A., Bidin, K., Tych, W., 2001. Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest. Plant Ecol. 153, 215–229.

Chappell, N.A., Douglas, I., Hanapi, J.M., Tych, W., 2004a. Source of suspended-sediment within a tropical catchment recovering from selective logging. Hydrol. Process. 18, 685–701.

Chappell, N.A., Nik, A.R., Yusop, Z., Tych, W., Kasran, B., 2004b. Spatially-significant effects of selective tropical forestry on water, nutrient and sediment flows: a modelling-supported review. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 513–532.

Chappell, N.A., Bidin, K., Sherlock, M.D., Lancaster, J.W., 2004c. Parsimonious spatial representation of tropical soils within dynamic, rainfall-runoff models. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 756–769.

Conway, S., 1982. Logging Practices. Miller Freeman Publications, San Francisco.

Croke, B.F.W., Merritt, W.S., Jakeman, A.J., 2004. A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. J. Hydrol. 291, 115–131.

Douglas, I., Spencer, T., Greer, T., Bidin, K., Sinun, W., Wong, W.M., 1992. The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah. Philos. Trans. Roy. Soc. Lond. Ser. B 335, 397–406.

Douglas, I., Greer, T., Sinun, W., Anderton, S., Bidin, K., Spilsbury, M., Jadda, S., Azman, S., 1995. Geomorphology and rainforest logging practices. In: McGregor, D.F.M., Thompson, D.A. (Eds.), Geomorphology and Land Management in a Changing Environment. Wiley, Chichester.

Douglas, I., Bidin, K., Balamurugam, G., Chappell, N.A., Walsh, R.P.D., Greer, T., Sinun, W., 1999. The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. Phil. Trans. Roy. Soc. Lond. B. 354, 1749–1761.

Dubreuil, P.L., 1985. Review of field observations of runoff generation in the tropics. J. Hydrol. 80, 237–264.

Elliot, W.J., Tysdal, L.M., 1999. Understanding and reducing erosion from insloping roads. J. Forest. 97, 30–34.

Eschenbach, C., Glauner, R., Kleine, M., Kappen, L., 1998. Photosynthesis rates of selected tree species in lowland dipterocarp rainforest of Sabah, Malaysia. Trees-Struct. Funct. 12, 356–365.

Fawcett, C.P., Young, P.C., Feyen, H., 1997. Validation of Data-Based Mechanistic non-linear rainfall-flow model. In: Proceedings of the Twelfth International Conference on Systems Engineering, ICSE'97, Coventry University, UK, 9-11 September 1997, Coventry University, Coventry, pp. 252–257.

Forestry Department Peninsular Malaysia, 1999. Specification of Forest Roads for Peninsular Malaysia. Forestry Department Peninsular Malaysia, Kuala Lumpur.

Gregory, K.J., Walling, D.E., 1973. Drainage Basin Form and Process. Arnold, London.

Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union 14, 446–460.

Hundecha, Y., Bardossy, A., 2004. Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model. J. Hydrol. 292, 281–295.

Jones, J.A., Grant, G.E., 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Res. 32, 959–974.

Kirkby, M.J., 1975. Hydrograph modelling strategies. In: Peel, R., Chisholm, M., Haggett, P. (Eds.), Process in Physical, Human, Geography. Heinemann, pp. 69–90.

Knapp, B.J., 1970. Patterns of water movement on a steep upland hillside, Plynlimon, central Wales. PhD Thesis, University of Reading, unpublished.

Kumagai, T., Katul, G.G., Saitoh, T.M., Sato, Y., Manfroi, O.J., Morooka, T., Ichie, T., Kuraji, K., Suzuki, M., Porporato, A., 2004. Water cycling in a Bornean tropical rain forest under current and projected precipitation scenarios. Water Resources Res. 40 (1) art. no. W01104.

Klemes, V., 2000. Common Sense and Other Heresies: Selected Papers on Hydrology and Water Resources Engineering. Canadian Water Resources Association, Cambridge.

Kuraji, K., 1996. Hydrological characteristics of moist tropical forests. Bull. Tokyo Univ. Forests 95, 93–208.

Malmer, A., 1996. Hydrological effects and nutrient losses of forest plantation establishment on tropical rainforest land in Sabah, Malaysia. J. Hydrol. 174, 129–148.

McDonnell, J.J., 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrol. Process. 17, 1869–1875.

Moreira, M.Z., Sternberg, L.D.L., Martinelli, L.A., Victoria, R.L., Barbosa, E.M., Bonates, L.C.M., Nepstad, D.C., 1997. Contribution of transpiration to forest ambient vapour based on isotopic measurements. Global Change Biol. 3, 439–450.

Moura-Costa, P., Karolus, A., 1992. Timber extraction volumes (1970–1991) of Ulu Segama Forest Reserve. Innoprise Corporation Sdn Bhd., Kota Kinabalu.

Moura-Costa, P.H., Yap, S.W., Ong, C.L., Ganing, A., Nussbaum, R., Mojiun, T., 1996. Large scale enrichment planting with dipterocarps as an alternative for carbon offset -methods and preliminary results. In: Appanah, S., Khoo, K.C. (Eds.), Proceedings of the Fifth Round Table Conference on Dipterocarps, Chiang Mai, Thailand, November 1994, Forest Research Institute of Malaysia (FRIM), Kepong, pp. 386–396.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. Part I. A discussion of principles. J. Hydrol. 10, 282–290.

Noguchi, S., Rahim Nik, A., Tani, M., 2003. Rainfall characteristics of tropical rainforest at Pasoh Forest Reserve, Negeri Sembilan, Peninsular Malaysia. In: Okuda, T., Manokaran, N., Matsumoto, Y., Niiyama, K., Thomas, S.C., Ashton, P.S. (Eds.), Pasoh: Ecology of a Lowland Rain Forest in Southeast Asia. Springer, Tokyo, pp. 51–58.

Noguchi, S., Abdul Rahim, N., Negeshi, J.N., Sasaki, S., Abdul Salam, A.C., 2004. Overland flow pathways at Hopea Odorata Plantation in Peninsular Malaysia. In: Sidle, R.C., Tani, M., Nik, A.R., Tadese, T.A. (Eds.), Forests and Water in Warm, Humid Asia. Disaster Prevention Research Institute, Uiji, pp. 208–210.

Nussbaum, R., Anderson, J.M., Spencer, T., 1995. Factors limiting the growth of indigenous tree saplings planted on degraded rainforest soils in Sabah, Malaysia. For. Ecol. Manage. 74, 149–159.

Ott, B., Uhlenbrook, S., 2004. Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model. Hydrol. Earth Syst. Sci. 8, 62–78.

Parkinson, S.D., Young, P.C., 1998. Uncertainty and sensitivity in global carbon cycle modelling. Clim. Res. 9, 157–174.

Pinard, M.A., Putz, F.E., Tay, J., Sullivan, T.E., 1995. Creating Timber Harvest Guidelines for a Reduced-Impact Logging project in Malaysia. J. Forest. 93, 411–445.

Pinard, M.A., Barker, M.G., Tay, J., 2000. Soil disturbance resulting from bulldozer-yarding of logs and post-logging forest recovery on skid trails in Sabah, Malaysia. For. Ecol. Manage. 130, 213–225.

Rhee, H., Fridley, J.L., Foltz, R.B., 2004. Modeling erosion from unpaved forest roads at various levels of geometric detail using the WEPP model. Trans. ASAE 47, 961–968.

Roberts, J., 2000. The influence of physical and physiological characteristics dof vegetation on their hydrological response. Hydrol. Process. 14, 2885–2901.

Sidle, R.C., Sasaki, S., Otsuki, M., Noguchi, S., Nik, A.R., 2004. Sediment pathways in a tropical forest: effects of logging roads and skid trails. Hydrol. Process. 18, 703–720.

Sherlock, M.D., Chappell, N.A., McDonnell, J.J., 2000. Effects of experimental uncertainty on the calculation of hillslope flow paths. Hydrol. Process. 14, 2457–2471.

Sinun, W. 1991. Hillslope hydrology, hydrogeomorphology and hydrochemistry of an equantorial lowland rainforest, Danum Valley, Sabah, Malaysia. PhD Thesis, University of Manchester, Manchester (UK), unpublished.

Sinun, W., Meng, W.W., Douglas, I., Spencer, T., 1992. Throughfall, stemflow, overland flow and throughflow in the Ulu Segama rain forest, Sabah, Malaysia. Philos. Trans. Roy. Soc. Lond. Ser. B. 335, 389–395.

Thang, H.C., 1987. Forest management-systems for tropical high forest, with special reference to Peninsular Malaysia. For. Ecol. Manage. 21, 3–20.

Thang, H.C., Chappell, N.A., 2004. Minimising the hydrological impact of forest harvesting in Malaysia's rainforests. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 852–865.

Thomas, R.B., Megahan, W.F., 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. A second opinion. Water Resources Res. 34, 3393–3403.

Tukey, J.W., 1961. Discussion emphasizing the connection between analysis of variance and spectrum analysis. Technometrics 3, 191.

Van der Plas, M.C., Bruijnzeel, L.A., 1993. The impact of mechanized selective logging of lowland rain forest on topsoil infiltrability in the upper Segama area, Sabah, Malaysia. International Association of Hydrological Sciences. Publication no. 216, pp. 203–211.

Vertessy, R.A., Elsenbeer, H., 1999. Distributed modeling of stormflow generation in an Amazonian rain forest catchment: effects of model parameterization. Water Resources Res. 35, 2173–2187.

Viney, N.R., Sivapalan, M., 2001. Modelling catchment processes in the Swan-Avon River Basin. Hydrol. Process. 15, 2671–2685.

Whitehead, P.G., Wilson, E.J., Butterfield, D., Seed, K., 1998. A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): Part II-application to large river basins in south Wales and eastern England. Sci. Total Environ. 210/211, 559–583.

Young, P.C., 1984. Recursive Estimation and Time-Series Analysis. Springer–Verlag, Berlin.

Young, P.C., 1985. The instrumental variable method: a practical approach to identification and system parameter estimation. In: Barker, H.A., Young, P.C. (Eds.), Identification and System Parameter Estimation. Pergamon, Oxford, pp. 1–16.

Young, P.C., 1992. Parallel processes in hydrology and water quality. J. Inst. Water Environ. Manage. 6, 598–612.

Young, P.C., 1999. Data-Based Mechanistic modelling, generalized sensitivity and dominant mode analysis. Comput. Phys. Commun. 115, 1–17.

Young, P.C., 2001. Data-Based Mechanistic modelling and validation of rainfall-flow processes. In: Anderson, M.G., Bates, P.D. (Eds.), Model Validation: Perspectives in Hydrological Science. Wiley, Chichester, pp. 117–161.

Young, P., 2003. Top-down and data-based mechanistic modelling of rainfall-flow dynamics at the catchment scale. Hydrol. Process. 17, 2195–2217.

Young, P.C., Beven, K., 1994. Data-based mechanistic modelling and the rainfall-flow non-linearity. Environmetrics 5, 335–363.

Young, P.C., Chotai, A., Beven, K.J., 2004. Data-Based Mechanistic modelling and the simplification of environmental systems. In: Wainright, J., Mulligan, M. (Eds.), Environmental Modelling: Finding Simplicity in Complexity. Wiley, Chichester, pp. 371–388.

Ziegler, A.D., Giambelluca, T.W., Sutherland, R.A., Vana, T.T., Nullet, M.A., 2001. Horton overland flow contribution to runoff on unpaved mountain roads. A case study in northern Thailand. Hydrol. Process. 15, 3203–3208.