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Parsimonious modelling of water and suspended sediment flux from nested catchments affected by selective tropical forestry

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The ability to model the suspended sediment flux (SSflux) and associated water flow from terrain affected by selective logging is important to the establishment of credible measures to improve the ecological sustainability of forestry practices. Recent appreciation of the impact of parameter uncertainty on the statistical credibility of complex models with little internal state validation supports the use of more parsimonious approaches such as data-based mechanistic (DBM) modelling. The DBM approach combines physically based understanding with model structure identification based on transfer functions and objective statistical inference. Within this study, these approaches have been newly applied to rainfall–SSflux response. The dynamics of the sediment system, together with the rainfall–river flow system, were monitored at five nested contributory areas within a 44 ha headwater region in Malaysian Borneo. The data series analysed covered a whole year at a 5 min resolution, and were collected during a period some five to six years after selective timber harvesting had ceased. Physically based and statistical interpretation of these data was possible given the wealth of contemporary and past hydrogeomorphic data collected within the same region.

The results indicated that parsimonious, three-parameter models of rainfall–river flow and rainfall–SSflux for the whole catchment describe 80 and 90% of the variance, respectively, and that parameter changes between scales could be explained in physically meaningful terms. Indeed, the modelling indicated some new conceptual descriptions of the river flow and sediment-generation systems. An extreme rainstorm having a 10–20 year return period was present within the data series and was shown to generate new mass movements along the forestry roads that had a differential impact on the monitored contributory areas. Critically, this spatially discrete behaviour was captured by the modelling and may indicate the potential use of DBM approaches for (i) predicting the differential effect of alternative forestry practices, (ii) estimating uncertainty in the behaviour of ungauged areas and (iii) forecasting river flow and SSflux in terrain with temporal changes in rainfall regime and forestry impacts.

Keywords: erosion; hydrology; modelling; suspended sediment; transfer function; tropical forestry

1. INTRODUCTION

Terrain disturbance associated with selective tropical forestry has been shown to give rise to elevated flux of suspended sediment from South-East Asian river catchments (e.g. Bruijnzeel 1992; Douglas *et al.* 1992; Yusop & Suki 1994). As these river sediment data are areally integrated measures of the net effect of erosion and sedimentation at individual landforms, they are arguably spatially robust indicators of the ecological sustainability of different forestry operations (Putz 1994). Further, these flows of suspended sediment, or 'SSflux' (Webb & Walling 1982), travel downstream and sometimes inundate corals at estuary mouths (Gupta 1996). Understanding SSflux is, therefore, important to our comprehension of tropical forestry impacts on aquatic ecology within both upstream and downstream environments.

While the observation that most river suspended sediment is mobilized during rainstorms is well attested (e.g. Webb & Walling 1982), there remains considerable uncertainty about what are the most appropriate process descriptions. This is particularly true for tropical forest environments where there has been little process research (Bonell & Balek 1993; Bruijnzeel 1996). The uncertainty may be seen to arise, at least in part, from three key issues. First, complexity arises from the highly localized nature of the dominant sediment sources (or 'erosional landforms') relative to the size of typical 'experimental river catchments'; for example, even a large sediment source of a 0.2 ha road landslide occupies only 0.45% of

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the 44 ha Baru experimental catchment (Chappell *et al.* 1998*b*). This extreme spatial variability in sediment generation is, in part, related to the large natural variability in soil erodibility and topographic characteristics (Chappell *et al.* 1998*b*), but is also related to the very localized disturbance, of canopy and terrain, produced by 'selective timber harvesting' (Putz 1994).

The second issue giving rise to uncertainty arises from the fact that catchment models of SSflux typically invoke different process relationships and parameter types to simulate sediment movement from each category of erosional landform (for example, see De Roo 1993, De Ploey 1995; Wicks & Bathurst 1996). A wide range of different erosional landforms (e.g. gullies, landslides, natural pipes, channel collapses and road sections with surficial erosion) can be found within a single tropical forest catchment, particularly one subject to disturbance by selective forestry (Douglas *et al.* 1992; Balamurgan 1997). This means that very many different parameter types are required when such models are used to simulate catchment behaviour. This is important, as certainty in 'representative' parameter values identified by calibration reduces dramatically with increasing numbers of parameter types (Beven 1996). This problem is exacerbated by the large uncertainties associated with attempts to relate point measurements of the hydraulic or rheological properties of soil to the size of terrain element that such models require (Chappell *et al.* 1998*a*).

The third key issue giving rise to uncertainty in the characterization of erosional behaviour stems from the nature of the governing rainstorms themselves. Tropical rainfall is often localized and intense (Chappell *et al.* 1999)—thus leading to a 'flashy' hydrogeomorphic response (Bidin & Greer 1997). Furthermore, extreme rainfall events, with return periods of a few years to tens of years, produce a disproportionately large part of the annual or longer-term suspended sediment yield (Douglas *et al.* 1999).

The need for further work on the parameterization of SSflux from tropical catchments, the effects of scale on this parameterization, and the identification of the dominant forestry-related, erosional landform(s) has been stressed in several recent reviews (Bonell & Balek 1993; Putz 1994; Bruijnzeel 1996; Bonell 1998). Consequently, this study has sought to: (i) examine whether parsimonious model structures describing the translation of tropical rainfall to observed SSflux, and the closely associated river flow, can be identified; (ii) identify whether large changes in temporal SSflux (and river flow) behaviour result from small changes in terrain scale; (iii) identify the 'spatial representativeness' of the modelling results by understanding the statistical properties of the river flow and SSflux behaviour (i.e. averages and frequency distributions) and physical processes giving rise to these responses; and (iv) identify whether the modelling can add to our existing understanding of the dominant hydrogeomorphic processes within terrain disturbed by selective logging.

Achievement of these four aims should enable better forecasting of SSflux from catchments where SSflux is either gauged or ungauged. Concentrating on the temporal dynamics of different scales of contributory area, this analysis seeks to complement the more spatially explicit, exploratory analyses undertaken with digital terrain models and geographical information systems (e.g. De Roo 1993).

The preliminary dynamic modelling undertaken within this study aims to be parsimonious, where the simplest 'acceptable' model structure that 'explains most' of either the observed rainfall–river flow or rainfall–SSflux is identified first. Model structures defined as 'acceptable' are those which can be justified by physically based understanding of system behaviour (Franks *et al.* 1997; Young *et al.* 1997), and 'explains most' is defined as a model describing at least three-quarters of the variance ($\epsilon \geqslant 0.75$) in the observed river flow or SSflux, where

$$\epsilon = 1 - \frac{\sigma^2_{\mathrm{error}}}{\sigma^2_{\mathrm{obs}}}, \qquad (1)$$

and ϵ is the simplified Nash & Sutcliffe (1970) efficiency measure, $\sigma^2_{\mathrm{error}}$ is the variance in the model residuals, and σ^2_{obs} is the variance in the observed data. Such a parsimonious approach is chosen, given that (i) '... large, highly parameterized models cannot be justified statistically [given parameter interaction during calibration of a single output variable], and (ii) the normal response of high-order dynamic systems is governed mainly by those few eigenvectors [or model structures] which define the identifiable dominant modes of the system ...' (Young & Beven 1994, p. 335). Data-based mechanistic (DBM) modelling is one such parsimonious approach. The DBM technique combines physically based understanding of system behaviour with model structure identification based on linear transfer functions (TFs) and objective statistical inference (Young *et al.* 1997). Wheater *et al.* (1993) have classified all hydrological models into four categories: (i) metric (black box) models, (ii) conceptual models (e.g. TOPMODEL), (iii) physics-based models (e.g. SHE), and (iv) hybrid metric-conceptual models. Under this classification, the DBM model, like the IHACRES model (Jakeman & Hornberger 1993), is a type of hybrid metric-conceptual model. Within this approach, the simplest TF that has been applied to rainfall–river flow is the first-order, single-input, single-output linear model:

$$q(k) = \frac{P}{1 - \mathcal{R}z^{-1}} r(k - \delta), \qquad (2)$$

where $q(k)$ is the river flow at the time index k, $\mathcal{R}$ is the recession or lag parameter, P is the system production or gain parameter, z^{-1} is the backward shift operator (i.e. $z^{-i}r(k) = r(k - i)$), δ is the time-delay to the initial response, and r is the rainfall input (Young 1984). This model has been expanded to describe (i) higher-order rainfall–river flow behaviour caused by the presence of multiple catchment water pathways, and (ii) the nonlinear effects caused by subsurface water storage (Young & Beven 1994; Young *et al.* 1997). Within this study, approaches comparable to those previously applied to rainfall–river flow (Young & Beven 1994; Young *et al.* 1997) will be applied to the relationship between rainfall and SSflux. Given that SSflux is the product of the river flow and the suspended sediment concentration, rainfall–river flow will be modelled and the results compared with those for rainfall–SSflux.

Table 1. *Summary water flow and SSflux data*

(Annual records for sites 6, 3, 4TB and 6TA are not shown as site 6 was destroyed one day after installation on 4 December 1994 by a road landslide, while site 3, 4TB and 6TA logging systems were damaged by electrical storms. Capital letters (A–J) refer to the column labels.)

A: site	B: area (km^2)	C: scale	D: basin order	E: run-off (mm)	F: SSflux ($t\,km^{-2}\,yr^{-1}$)	G: SSflux (t)	H: G(x)/G(1) on 19 January 1996 (%)	I: SSflux (t)	J: I(x)/G(x) (%)
sites with permanent discharges									
1	0.441	catchment	3	1867	592	261	100	105	40.3
2-east	0.046	multi-grid	1	908	1467	67	39	33	49.2
2-middle	0.143	multi-grid	2	1684	685	98	36	40	41.0
2-west	0.190	multi-grid	2	1611	361	69	26	11	15.6
sites with intermittent discharges									
4	0.013	multi-grid	1	1162	643	8.4	3	1.1	12.8
5	0.0075	multi-grid	1	187	14	0.107	0.04	0.012	11.5
sites with ephemeral (storm-only) discharges									
3TB[a]	0.0006	grid	0	31	24	0.015	—	—	—
4TA[a]	0.00155	grid	0	60	81	0.126	—	—	—
5TA[a]	0.00145	grid	0	60	15	0.022	—	—	—
5TB	0.0014	grid	0	57	41	0.058	0.02	0.020	34.1
6TB[b]	0.0003	grid	0	78	99	0.030	0.01	0.010	31.1

[a] Data lost during 19 January 1996 rainstorm.
[b] Annual values extrapolated from eight months' data.

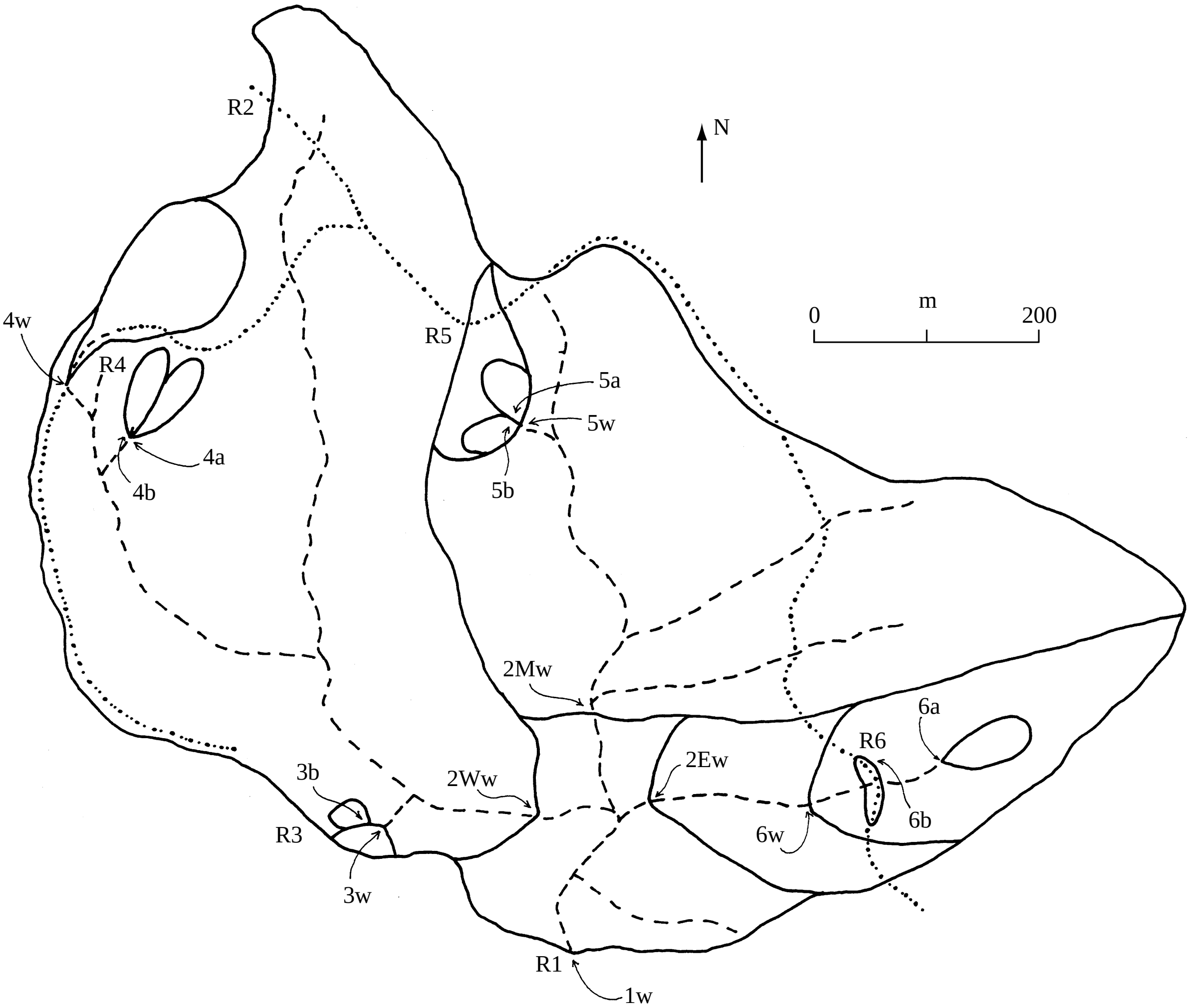

Figure 1. Nested subcatchment structure within the 44 ha Baru experimental catchment. The location of rain-gauges, weirs and tipping-bucket flow-gauges are shown with the symbols 'R', 'w', and 'a' or 'b', respectively. The catchment and subcatchment divides (solid lines), permanent streams (dashed lines) and lorry haulage roads (dotted lines) are also shown. E, east; M, middle; W, west. A map showing the catchment location within the region is given within Chappell *et al.* (1998*b*).

Synchronous data are available for several subcatchments 'nested' within our single experimental catchment (table 1, figure 1). Given the parsimonious and uncertainty framework adopted, analysis of these multiple time-series might allow scale- or process-related differences to be identified. Lastly, a DBM approach is achievable using data for the chosen experimental catchment because of the wealth of process-based and applied research that has been undertaken within this and neighbouring sites (e.g. Sinun *et al*. 1992; Sherlock 1997; Douglas *et al*. 1999).

2. MONITORED SITES

Our experimental site is 0.441 km^2 in area, is known as the 'Baru catchment' and lies to the north-east of the Danum Valley Field Centre (DVFC) in Sabah, Malaysian Borneo (5°01′ N and 117°48.75′ E).

(a) *Catchment properties*

The climate at DVFC is equatorial with modest annual seasonality but marked El Niño southern oscillation cycles (Chappell *et al*. 1999; Walsh & Newbery 1999) and has an 11 year (1986–1996) mean rainfall of 2778 mm. High rainfall intensities are relatively frequent with > 50 mm h^{-1} (maximum 5 min intensity) events having a return period of 23.3 days and in excess of 100 mm h^{-1} a return period of 139.6 days (Sherlock 1997). The study region is underlain by the Kuamut geological formation, which is a melange comprising largely mudstones and sandstones (Leong 1974; Clennell 1996). Recent physico-chemical analysis of the soil profiles (Chappell *et al*. 1998*b*), indicates that the FAO Haplic Alisol (Alh) unit dominates within the catchment. These are relatively unstable soils (Driessen & Dudal 1991; Chappell *et al*. 1998*b*), which were formerly classified (FAO-Unesco 1974; Wright 1975) with the more stable soils of the current Acrisol unit (FAO-Unesco 1990). Acrisol–Alisol soils are the dominant soils in lowland South-East Asia (FAO-Unesco 1990). Stratigraphical logs from numerous soil pits and roadside exposures indicate that the solum (i.e. the A and B soil horizons) is typically 1.5 m deep and overlies 1.5 m of weathered rock (i.e. C horizon).

The research catchment is covered by 'lowland dipterocarp rainforest' that is managed by the Forestry Upstream Division of Yayasan Sabah as part of their 9728 km^2 timber concession (Marsh & Greer 1992). The forest within the catchment was 'selectively logged' during 1988 and 1989. Timber extraction was by a 'selective' rather than a 'clearfell' logging system, and has the aim of producing a sustainable harvesting coupe every 30 years. A combination of tractor- and high-lead-yarding was used to extract the timber to the lorry haulage roads (Putz 1994), and left a dense forest cover that is typical of selectively logged forests throughout South-East Asia (Marsh & Greer 1992).

(b) *Subcatchment identification*

The catchment was chosen for study primarily as it had been the focus of process-based hydrological and geomorphic research since 1988 (Douglas *et al*. 1992). Prior to the installation of further instrumentation in 1995, a detailed survey of the active erosional landforms within the catchment was undertaken, followed by a helicopter survey of the canopy disturbance. While timber harvesting had ceased in 1989 and some regeneration of the canopy and terrain had taken place (Douglas *et al*. 1995), some erosional landforms associated with forestry activities were still present and included haulage road gullies, road culvert collapses, and eroding 'skid trails'. Skid trails are the unsurfaced paths used by tracked forestry vehicles ('skidders') to drag timber to the engineered 'roads' (either unsurfaced or surfaced with local chert) where lorries then haul timber to the sawmill. Natural erosional landforms including channel bank collapses and channel heads with soil piping (see Bidin 1995) were also observed.

For grid-based modelling of catchment systems, the terrain is typically split into hundreds or thousands of elements for which effective soil parameters are required (Chappell & Ternan 1992). Within the overall research programme, eight diverse subcatchments each having areas 260th (0.39%) to 3380th (0.0296%) the size of the whole Baru catchment (also called 'site 1') were selected and described as 'grid-scale' sites (figure 1, table 1). These subcatchment areas are more comparable in scale with individual erosional landforms (table 2) and included slope sections and channel heads. The grid-scale sites had only ephemeral flows, i.e. flows only during rainstorms, making these 'zero-order basins'.

Six larger subcatchment areas (half, third, 10th, 13th, 34th and 59th the size of the whole Baru catchment) were then identified (figure 1, table 1). Four of these sites (sites 2-east, 2-middle, 2-west and 6) experienced perennial channel discharge. In contrast, sites 4 and 5 had intermittent channel discharge, with dry periods at the end of long recessions. Site 4 was an 'artificial' contributing area, discharging along a 100 m gully cut within an unsurfaced haulage road. Field observations indicated that this gully received waters from (i) the indurated road itself, (ii) the roadside drain, (iii) upslope subsurface flows forced to return to the ground surface by the presence of the indurated road, and (iv) small upslope channel flows. All eight very small, grid-scale sites were contained within one or more of these larger subcatchments (known as multi-grid sites), so that a 'nested' catchment structure was achieved. The whole Baru catchment contains a 'third-order' channel system (Strahler method) as it contains two second-order streams (i.e. sites 2-middle and 2-west) which each contain at least two first-order streams (e.g. sites 4, 5 and 6).

Within this preliminary modelling study, only the data from contributory areas 1, 2-east, 2-middle, 2-west and 4 were simulated. Data from site 6 are excluded from the analyses, as the gauging structure was destroyed by a road landslide one day after installation on 4 December 1994. Data from site 5 are also not used for modelling as small gaps in the river flow record had to be filled by rating against other stations. The statistical and physically based interpretation of the data from the very small, ephemeral systems was, however, used to aid the understanding of differences between the first-, second- and third-order streams.

(c) *Sensors and monitoring*

All the contributory areas with permanent or intermittent flows were gauged at 120° thin-plate V-notch

Table 2. *Landform scales for active erosional features within the Baru catchment*

primary sediment source	area in plan (ha)
road landslide	0.25 (to 2[a])
mass wasting at road culverts	0.002
road gully	0.02
channel head	0.0005
channel banks	continuum

[a] And adjacent area.

weirs. These structures were built to a height of 1–2 m with zinc plate and concrete retaining walls and pinned into the solid bedrock. Weir water-level was measured with pressure transmitters, and the standard discharge rating adjusted with a programme of current metering and salt dilution gauging. In contrast, the channel head and slope locations with ephemeral flows (i.e. sites 3TB, 4TA, 4TB, 5TA, 5TB, 6TA and 6TB), were gauged with large tipping-bucket devices with a capacity of approximately 3 l. All tipping-bucket devices were individually calibrated.

At both types of gauging structure, Partech (Electronics) Ltd® IR15C turbidity probes were installed to derive 'suspended sediment concentration' continuously. In the case of the tipping-bucket structures, the turbidity probes were installed within the zinc approach flumes. This turbidity probe approach to suspended sediment monitoring was chosen in preference to the use of 15 event-triggered, automatic liquid samplers for two reasons. First, continuous turbidity monitoring reduces the risk of missing or underrepresenting data for extreme events (Kronvang *et al.* 1997). Second, the very 'flashy' nature of the streams within the DVFC area (Bidin & Greer 1997) and elsewhere within the tropics, may mean that high-resolution sampling (i.e. every 5 min) is required for accurate dynamic modelling (Young 1984). Such a high sampling rate would make the traditional sampling-plus-filtration method unrealistic for so many sites. An intensive programme of spot water sampling for suspended sediment concentration was, however, undertaken at all sites to improve the calibration of the turbidity probes (following Clifford *et al.* 1995).

The highly localized, convective nature of tropical rainfall (e.g. Chappell *et al.* 1999) necessitated the use of six tipping-bucket rain-gauges to measure the catchment average rainfall. Thiessen polygons were used for the averaging process. Gauges at sites R1, R3, R4 and R6 (figure 1) were placed on ironwood towers up to 6 m in height to prevent attack from wild boar or cover by regenerating vegetation, while the exposed site R5 gauge was located within a 2 m high and 5 m diameter chert–concrete wall to prevent elephant attack.

All rainfall, water-level and turbidity sensors were data logged, and the loggers interrogated on at least a weekly basis ensuring regular checks of the structures and sensors. Sampling of the variables of time-integrated rainfall (mm), instantaneous river flows ($\mathrm{m^3\,s^{-1}\,km^{-2}}$) and instantaneous SSflux ($\mathrm{kg\,s^{-1}\,km^{-2}}$) was for every 5 min over the core 12 month period from 1 July 1995 to 30 June 1996, thus giving 105 408 values per measured variable. Data concatenation, rating and subsequent modelling was undertaken using the Matlab® programming environment (Mathworks, Inc.).

3. *A PRIORI* BEHAVIOURAL CHARACTERISTICS

Before attempting to identify the form of the DBM models that describe the generation of river flow or SSflux from rainfall, some understanding of the behavioural characteristics of these systems is required (Young & Beven 1994). Such *a priori* analyses seek to identify locally important physical processes and the likely 'representativeness' of the responses. Bruijnzeel (1992) and Evans (1997) recently stressed the importance of understanding whether sediment data series are 'representative' of periods including geomorphologically active, extreme rainstorms.

(a) *Spatial variability in annual rainfall, river flow and SSflux*

The average rainfall received by the six catchment gauges from 1 July 1995 to 30 June 1996 was 2956 mm with a modest spatial coefficient of variation (CV) of 10.1%. This indicates a slightly wetter period in comparison with the 11 year mean of 2778 $\mathrm{mm\,yr^{-1}}$ (± 312 mm σ or 11.5% temporal CV) for the nearby DVFC rain-gauge.

The water flow passing through the site 1 weir totalled 1867.1 mm, indicating a 'run-off coefficient' (defined as the percentage of rainfall transferred to surface water flow) of 63%. The run-off coefficients for the slightly smaller, second-order sites of 2-middle and 2-west fell to 57 and 54%, respectively, while first-order sites 2-east, 4 and 5 generated only 30, 39 and 6%, respectively, indicating an increasing loss of site waters by subsurface pathways as surface contributing-area decreases (see Bidin 1995). The very small run-off coefficients for slope-only contributory areas of 3TB, 4TA, 5TA and 5TB of 1.0, 2.0, 2.0 and 1.9%, respectively, probably result from an absence of returning subsurface flow, that dominates the behaviour of the contributory areas having perennially flowing channels (Sherlock 1997; Chappell *et al.* 1998*a*). The small amounts of surface flow observed at these slope-only sites are comparable with the proportions of infiltration-excess overland flow (IOF) (Horton 1933) observed on other slopes within the region (Sinun *et al.* 1992; N. A. Chappell, unpublished data). The exception to this is slope site 6TB, where greater surface flow is observed from the very indurated haulage road that comprises much of the contributing area to this site. The smaller run-off coefficients for most of the zero-order areas are, therefore, expected to give a smaller SSflux per unit area (where SSflux = water flow × suspended sediment concentration).

The total SSflux from the whole Baru catchment (site 1) over the year 1995–1996 was 592 $\mathrm{t\,km^{-2}\,yr^{-1}}$. This flux is considerably lower than that monitored for the site over the logging and immediate post-logging period (mid-1988 to mid-1990) of 1600 $\mathrm{t\,km^{-2}\,yr^{-1}}$ (Douglas *et al.* 1992) indicating that some recovery of the terrain had taken place. For reference, the yield of a nearby morphometrically similar, but undisturbed catchment was 312 $\mathrm{t\,km^{-2}\,yr^{-1}}$ over the earlier period (Douglas *et al.* 1992).

Over the 1995–1996 period, the five first- and second-order sites generated between 14 and 1467 t km^{-2} yr^{-1} with a spatial CV of 85% (table 1). The five zero-order basin fluxes ranged from only 15 to 99 t km^{-2} yr^{-1} with a spatial CV of 70% (table 1). Clearly, the limited number of zero-order sites of non-logged slopes (site 3TB), ephemeral channels (sites 5TA, 5TB), and poorly indurated skid trails (site 4TA) are not the dominant source of sediments observed at the scale of the whole catchment. In contrast, the catchment average response lies within the variability observed at the scale of the first- and second-order basins. This justifies focusing the preliminary modelling on the behaviour on the first-, second- and third-order basins.

Some assurance of the reliability of the SSflux data (c.f. Kondolf & Matthews 1991) is gained from the observation that the second-order regions of 2-east, 2-middle and 2-west, which comprise 86% of the third-order Baru catchment and probably most of the primary sources, yield only 10% less annual sediment flux (234 t) in comparison with that recorded at the site 1 gauge (261 t).

Site 2-west generated relatively modest SSflux in comparison with site 2-east and 2-middle, despite including (i) the highest degree of canopy disturbance and (ii) site 4 which generates 643 t km^{-2} yr^{-1} SSflux from a severely gullied haul road, though only occupying 7% of the 2-west area. The 4.6 ha site 2-east generated a high SSflux per unit area as a result of a combination of remobilization of sediment from a 0.3 ha road landslide that occurred on 4 December 1994 (that buried weir 6), and a new, adjacent 0.2 ha road landslide that occurred on 19 January 1996. This site did in fact contribute 25.8% of the suspended sediment mass passing weir 1 while occupying only 10.4% of Baru catchment area. Site 2-middle generated a slightly higher SSflux (685 t km^{-2} yr^{-1}) than the average catchment response, and qualitative field observations indicated that this site was strongly influenced by soil collapse at two road culverts during the storm of 19 January 1996.

(b) *Temporal variability in annual SSflux behaviour: presence of extreme events*

The 19 January 1996 rainstorm produced the highest daily rainfall (167 mm) on record at DVFC (1986–1996) and a return period of 10–20 years (Douglas *et al*., this issue). Some 105 t or 40.3% of the annual SSflux from the whole Baru catchment was generated (table 1). The importance of these extreme events to sediment load has been noted by previous studies undertaken at this (Douglas *et al*. 1992) and other sites (e.g. Webb & Walling 1982) and underlines the importance of continuous rather than spot sampling that might inadequately characterize such events. The presence of these short periods of high SSflux within the records does not, however, necessarily imply that the hydrological-erosional system is either 'nonlinear', where parameters of a linear model, change with storm size, or 'non-stationary', where the form of the relationship between the rainfall and SSflux changes even with the same storm size (Young 1984). The activation of new primary sediment sources within the catchment, as a result of, for example, slope failures during extreme events might be expected to enhance the nonlinearity and non-stationarity of the rainfall–SSflux behaviour relative to the rainfall–river flow behaviour.

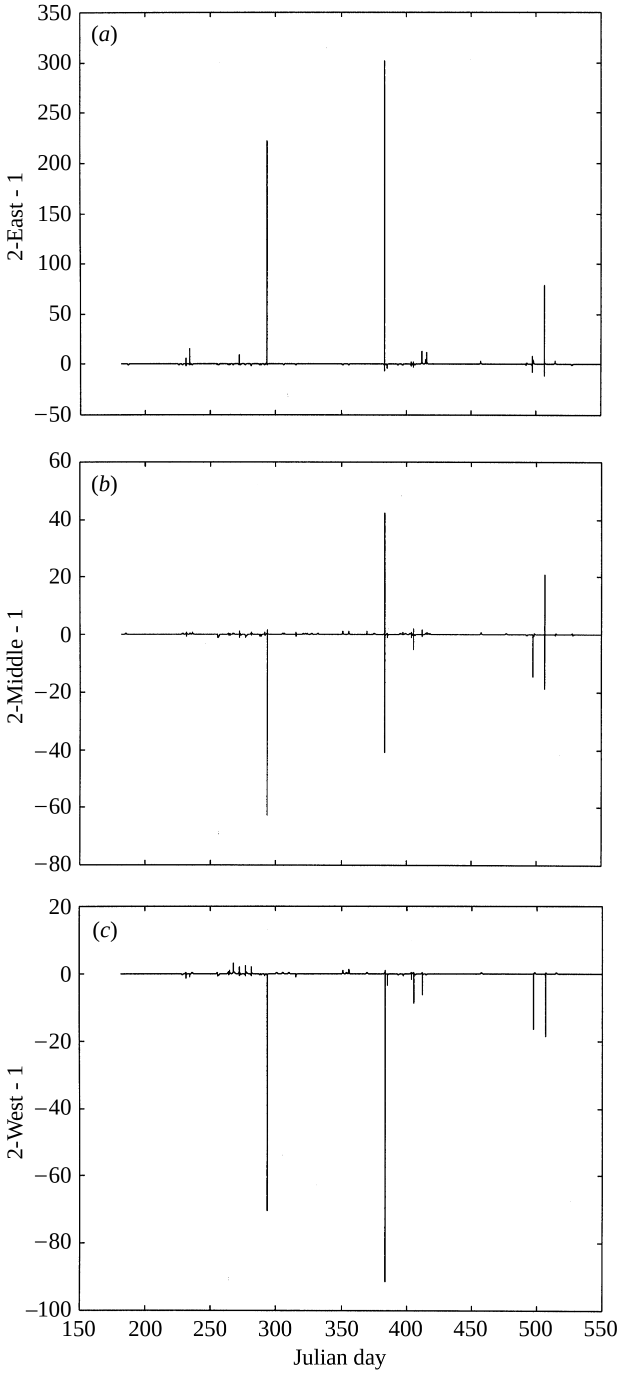

Figure 2. Plots showing the difference between the instantaneous SSflux (kg s^{-1} km^{-2}) recorded every 5 min from (*a*) subcatchment 2-east, (*b*) subcatchment 2-middle, and (*c*) subcatchment 2-west, and that from the whole Baru catchment. The time ordinate in Julian days, where day 1 is 1 January 1995.

By subtracting the catchment-average SSflux from that produced by individual subcatchments: (i) the activation of major new sediment sources, (ii) the location of those new sources, and (iii) remobilization of sediments from major sediment sources can be seen. For example, the first large positive peak (on 21 October 1995) in figure 2*a* probably relates to remobilization of sediments from the 4 December 1994 landslide in site 2-east, either from in-channel storage or the landslide-toe (by the stream), during high flow conditions. The second positive peak in

Table 3. *First-order, nonlinear TF model efficiencies, calibrated and derived parameters for rainfall–river flow. The efficiencies for the linear models and for the nonlinear models with term β fixed to that of the whole catchment are also shown within the second and third columns*

(TC, time constant; ssP, steady-state production.)

site	ϵ linear model	$\mathcal{R}$ when β fixed at 0.420 (nonlinear)	ϵ nonlinear model	parameters of the nonlinear model (site-specific β): β	$\mathcal{R}$	P	δ	TC (min)	ssP
sites with permanent discharges									
1	0.489	−0.8983	0.802	0.420	−0.8983	0.1045	2	46.6	1.0275
2-east	0.407	−0.8786	0.661	0.425	−0.8775	0.0429	1	38.3	0.3500
2-middle	0.490	−0.8974	0.793	0.420	−0.8974	0.0942	2	46.2	0.9186
2-west	0.483	−0.8768	0.884	0.415	−0.8781	0.1231	2	38.4	1.0092
site with intermittent discharges									
4	0.545	−0.9147	0.777	0.343	−0.9231	0.0640	1	65.5	0.8322

the same figure relates to the new road landslide triggered on 19 January 1996, and the last (smaller) positive peak relates to remobilization of sediments from the same January landslide. In contrast, the other important source, site 2-middle, generated a positive anomaly related to the failure of two road culverts during the extreme rainfall of 19 January 1996, but with no anomaly on 21 October 1995 as at that time site 2-middle lacked sediments for remobilization (figure 2*b*). Examination of the data for site 2-west demonstrates that while the greatest 5 min SSflux was generated during the 19 January 1996 event, the anomaly was negative (figure 2*c*), indicating that the whole Baru catchment contained new, regionally significant sources while site 2-west did not. The greater proportion of the annual SS yield at sites 2-east and 2-middle generated during the 19 January 1996 event (i.e. 49.2 and 41%, respectively) in comparison with site 2-west (15.6%) also supports the idea of new sources being activated in these two areas (table 1).

Given the importance of extreme events to annual (table 1, figure 2) and longer-term SSflux behaviour (Douglas *et al.*, this issue), it is critical that the accepted DBM model structures are able to characterize the behaviour of periods including these extreme rainstorms. Furthermore, it is important that the models are able to represent those contributory areas that generate large, new sediment sources during extreme events, i.e. sites 1, 2-east and 2-middle.

(c) *Time-independent series analysis*

Prior to an examination of the time-dependent rainfall, water flow and suspended sediment relationships implicit within dynamic modelling, the characteristics of these data are analysed as time-independent series.

The frequency behaviour of the flows from the whole, third-order catchment can be compared with those from the first- and second-order subcatchments. The flow duration curves for the subcatchments with perennial water flows (i.e. from figure 3*a* sites 2-east and 2-middle and 2-west) exhibited a similar frequency distribution to that of the whole catchment. In some contrast, the subcatchment with intermittent flows (i.e. site 4) shows a slightly less 'flashy' flow regime at high flows and site 4 also shows a rapid loss of low flows.

The sediment duration curves (Webb & Walling 1982) for site 2-east should not be interpreted for times of low SSflux given that data were removed as a result of the turbidity sensor problems during low flows. The data for the other sites (i.e. sites 1, 2-middle, 2-west and 4) indicate a similar distribution of low sediment flows

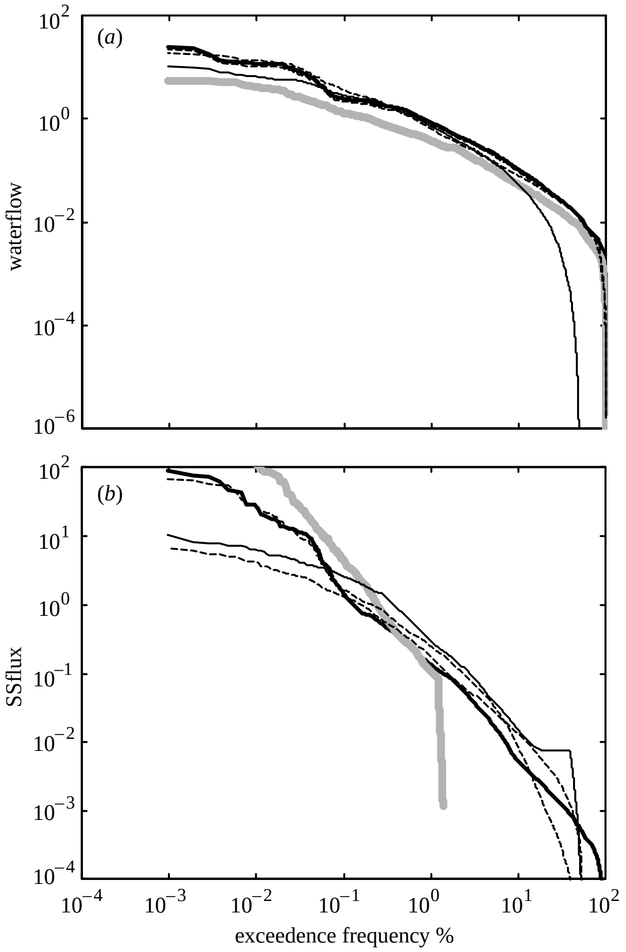

Figure 3. Flow and sediment duration curves for (*a*) water flows, and (*b*) SSflux. The broad black line shows data for the whole Baru catchment (site 1), site 4 data is shown with a narrow black line, while the broad grey line shows data for site 2-east. The dotted lines show data for sites 2-middle and 2-west. Water flows are instantaneous flows ($\mathrm{m^3\,s^{-3}\,km^{-2}}$) recorded on a 5 min basis, while SSflux is instantaneous SSflux ($\mathrm{kg^{-1}\,km^{-2}}$) also recorded on a 5 min basis.

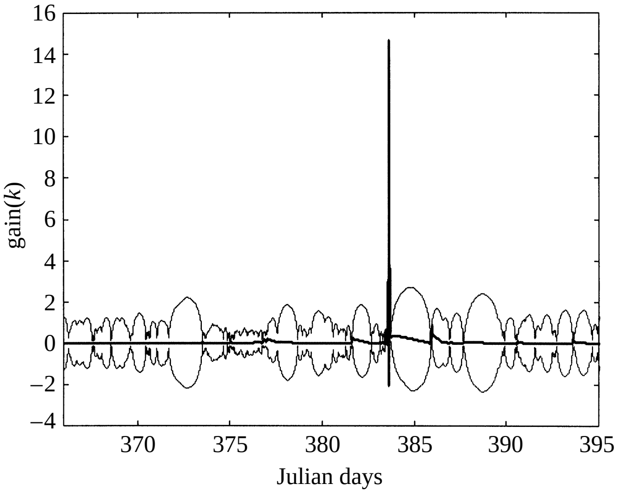

Figure 4. The time-variable production, P, estimates for a whole year of 5 min, rainfall–SSflux data measured at site 1 plotted against time in Julian days, where day 1 is 1 January 1995. Only data for January 1996 (day 366–395) are shown, so that the variation in the standard error of the estimate (thinner lines) can be seen.

(figure 3*b*). In contrast, during periods of highest SSflux, the behaviour diverged, with site 2-east containing the 0.2 and 0.3 ha landslides generating considerably more SSflux. One might infer from this that differences between first- and second-order contributory areas become apparent during periods of high hydrogeomorphic activity, either at the peak of storms or during extreme rainstorms.

Simple linear correlation of river flow and SSflux with the 5 min rainfall that generates these flows yields extremely low efficiencies (as defined in equation (1)) of between 0.05 and 0.07 for the rainfall–river flow relationship applied to all first- to third-order sites, and between 0.02 and 0.07 for the rainfall–SSflux relationship applied to the same sites. This poor efficiency results from lags and nonlinearities that themselves result from the effect of antecedent conditions and, therefore, demonstrates the need for dynamic modelling.

4. DYNAMIC MODELLING

Following the identification of *a priori* behavioural characteristics that might be pertinent to the acceptability of the TF models to be identified, evidence of nonlinearity within the rainfall to river flow and SSflux was first sought using time-variable parameter (TVP) estimation.

(a) *State-dependent TF modelling*

Within this study TVP estimation is undertaken with a dynamic linear regression model (Young 1993) incorporating a first-order TF applied to rainfall–river flow and rainfall–SSflux for the third-order stream data. Following Young & Beven (1994) the system production, P, was allowed to vary, while the recession parameter, $\mathcal{R}$, was held nearly constant by minimizing the noise variance ratio parameter. The resultant state-dependent model (SDM) that was produced describes the rainfall–river flow response with an efficiency of 0.9934 and the rainfall–SSflux with an efficiency of 0.9871. The SDM, therefore, captures almost all of the nonlinearity and

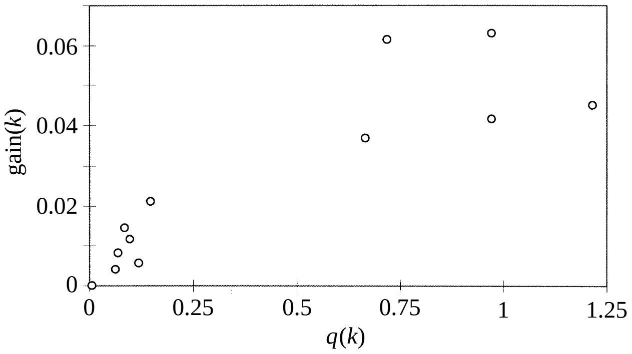

Figure 5. The most significant estimates of Pk (i.e. those with the smallest standard error) plotted against the observed, instantaneous river flow ($\mathrm{m^3\,km^{-2}}$), $q(k)$, measured as site 1.

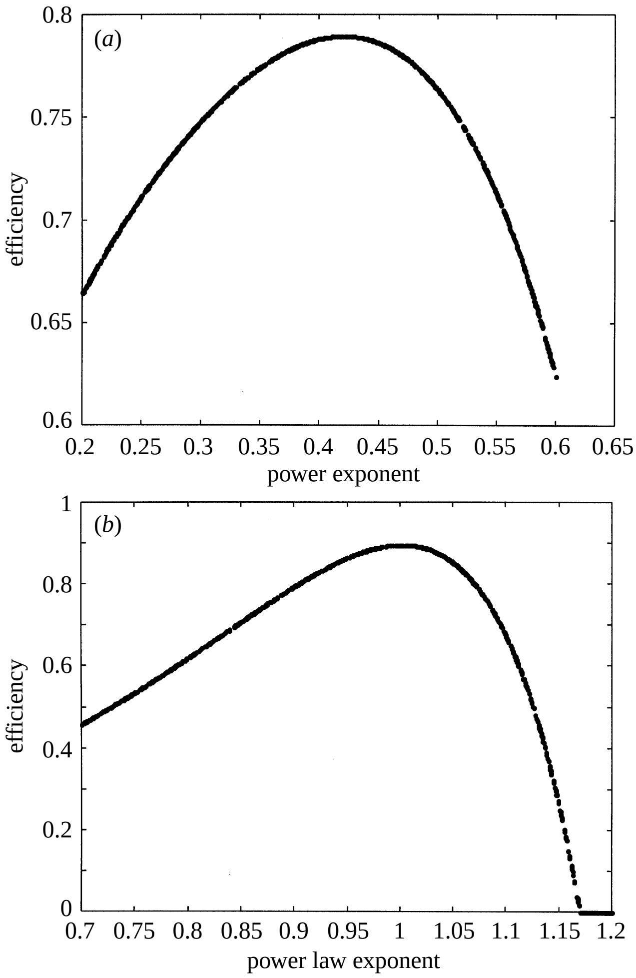

Figure 6. Final optimization of the power-law exponent characterizing the effective rainfall nonlinearity in (*a*) rainfall–river flow system, and (*b*) rainfall–SSflux system of the whole Baru catchment.

non-stationarity in the rainfall–river flow and rainfall–SSflux behaviour.

The temporal dynamics of the time-variable production (gain) parameter, P, within the rainfall–SSflux SDM are shown in figure 4 for an example subset of the modelled period. By plotting the most significant (i.e. low standard error) estimates of the TVP against the measured river flow (e.g. figure 5) and measured SSflux,

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Table 4. *First-order, nonlinear TF model efficiencies, calibrated and derived parameters for rainfall–SSflux. The efficiencies for the linear models and for the nonlinear models with term β fixed to that of the whole catchment are also shown within the second and third columns*

site	ϵ linear model	$\mathcal{R}$ when β fixed at 1.000 (nonlinear)	ϵ nonlinear model	parameters of the nonlinear model (site-specific β)					
				β	$\mathcal{R}$	P	δ	TC (min)	ssP
sites with permanent discharges									
1	0.131	−0.2406	0.8958	1.000	−0.2406	0.2870	0	3.51	0.3780
2-east	0.122	−0.5010	0.8816	1.000	−0.5010	0.6575	0	7.24	1.3175
2-middle	0.128	−0.1808	0.8247	1.000	−0.1808	0.2710	0	2.92	0.3308
3-west	0.181	−0.0099	0.7700	1.030	−0.0038	0.0981	0	0.90	0.0985
site with intermittent discharges									
4	0.297	−0.8154	0.4640	0.960	−0.8201	0.0367	0	25.21	0.2040

the production parameter can be seen to increase with increasing river flow or SSflux. This is a clear indication of nonlinearity within the water and sediment behaviour. Figure 5 suggests a power-law relationship for the river flow generation within our tropical catchment. Power-law relationships are common within hydrological and sedimentological modelling, and for rainfall–river flow are usually explained by the nonlinear effects of subsurface water storage (Young & Beven 1994). The exponent of the power law, β, optimized by separate Monte Carlo analysis is 0.420 (figure 6*a*). Comparison with the power exponent of 0.645 derived for river flow generation within a 72 ha temperate catchment in Wales (Young & Beven 1994) indicates that river flow generation within the Baru catchment is less sensitive to the antecedent conditions. Given the understanding that the Baru river flow is generated mostly by emerging subsurface flow (Sherlock 1997; Chappell *et al.* 1998*a*), the smaller effect of antecedent conditions may be explained by smaller subsurface water storage, i.e. the river hydrograph more closely approximates the rain graph. The nonlinearity, as expressed by term β, within the perennial subcatchment rainfall–river flow was very similar to that of the whole catchment (table 3). The intermittent stream of site 4 did, however, exhibit smaller nonlinearity, probably due to a greater proportion of purely surface flow, giving a reduced effective storage.

If the same form of power-law relationship is used to describe the nonlinearity within the rainfall–SSflux response, the power exponent increases to 1.000 (figure 6*b*) indicating a high sensitivity to antecedent conditions. While some of this effect relates to the nonlinearity in the production of the river flow that transports the suspended sediment, there are additional causes such as the nonlinear relationship between: (i) rainfall and soil particle detachment on slopes (Bennett 1974), (ii) river discharge and the shear stress that entrains in-channel sediments, and (iii) when considering the spatially integrated effect of several mass movements, the relationship between increasing soil water and reduced soil strength. As with the rainfall–river flow, the nonlinearity within the perennial subcatchment rainfall–SSflux was very similar to that of the whole catchment (table 4). The intermittent stream did, however, exhibit slightly smaller sensitivity to antecedent conditions (β was 0.960), which may relate to the field observation that mass movements and significant in-channel sediment stores were not present within the shallow channel that directed water from this site.

The two nonlinear relationships identified can be used to transform the rainfall input, leaving a linear TF between the transformed rainfall, or 'effective rainfall' (r_{eff}), and the river flow or SSflux, where

$$r_{\mathrm{eff}}(k) = r(k)(s(k))^{\beta}, \tag{3}$$

in the case of the rainfall–SSflux relationship. Term $r(k)$ is the catchment-average rainfall at time index k, $s(k)$ is SSflux at time index k, and β is the estimate of the power-law exponent (after Young & Beven 1994). In order to maintain mass balance, the effective rainfall estimate, $r_{\mathrm{eff}}(k)$, is normalized in relation to the catchment-average rainfall to give the normalized effective rainfall, $r_{\mathrm{e}}(k)$, where

$$r_{\mathrm{e}}(k) = r_{\mathrm{eff}}(k)\left(\frac{\sum r(k)}{\sum r_{\mathrm{eff}}(k)}\right), \tag{4}$$

Applying an $r_{\mathrm{e}}(k)$ submodel within sediment modelling, as in river flow modelling, had been suggested in the earlier conceptual work of Bennett (1974). The $r_{\mathrm{e}}(k)$ submodel (for rainfall–river flow and rainfall–SSflux) applied within this initial study is, however, only the first step in the development of more robust $r_{\mathrm{e}}(k)$ submodels based solely on the rainfall as within the Bedford Ouse model (Young 1974), or on a combination of rainfall and an internal state variable such as soil moisture or piezometric surface (Fawcett *et al.* 1997).

(b) *First-order, 'nonlinear' versus linear TF modelling*

The impact of incorporating the 'effective rainfall' nonlinearity on the efficiency of rainfall–river flow and rainfall–SSflux models was then investigated. The parameters of first-order (i.e. single P and $\mathcal{R}$ parameters) TF models were estimated using the recursive technique known as the simplified refined instrument variable (SRIV) algorithm (Young 1985). This modelling was attempted for data series integrating the behaviour of the whole third-order catchment and the first- and second-order streams (i.e. sites 2-east, 2-middle, 2-west and 4). The whole 12 month period, including all 105 408 five minute samples for each variable, was modelled.

The results of the first-order, rainfall–river flow modelling are shown in table 3, while those for the rainfall–SSflux modelling are shown in table 4. By incorporation of the nonlinearity, the efficiency of the rainfall–river flow models increased from a range of 0.41–0.55 to a range of 0.66–0.88 (table 3). More specifically, the efficiency of the river generation model for the whole catchment (site 1) increased from 0.49 to 0.80. The improvements in the more strongly nonlinear rainfall–SSflux response were even larger, with efficiency of the sediment generation model for the whole catchment increasing from 0.13 to 0.90, and for the subcatchment areas an increase from a range of 0.12–0.30 to 0.46–0.88 was possible (table 4). The first-order TF model (with no initial delay) that describes 90% of the variance in the rainfall to SSflux behaviour of the whole catchment is given as

$$s(k) = \frac{0.2870}{1 - 0.2406z^{-1}} r_{\mathrm{e}}(k), \tag{5}$$

Further analyses aim to build on the success of models incorporating the nonlinearities characterized by the $r_{\mathrm{c}}(k)$ submodel.

(c) *Estimation of parameter uncertainty*

Within § 1, it was noted that calibrated models with large numbers of parameter types result in high model efficiencies that can be generated by many different combinations of parameter values. This is also the case for calibrated models conditioned by point scale, field measurements as such data are often characterized by a high degree of stochastic, spatial heterogeneity and are often unrepresentative of larger-scale behaviour (Beven 1996; Chappell *et al.* 1998*a*). Meaningful comparison of model-derived parameter values in such circumstances is probably unrealistic (Beven 1996). Even within parsimonious modelling techniques and the identification of high model efficiencies, parameter interaction will exist and thereby affect the degree of parameter interpretation possible.

Within this study, parameter uncertainty was explored by running 10 000 Monte Carlo realizations of the first-order, nonlinear TF model with $\mathcal{R}$ and P parameter values sampled from a random uniform distribution (following Franks *et al.* 1997; Chappell *et al.* 1998*a*). The 5 min data series of river flow and SSflux for the whole year were used, together with a single month of river flow data for comparison. Figure 7 shows the results of the realizations undertaken with one year's data. Both the rainfall–river flow and rainfall–SSflux show single optima (i.e. a single peak) in the resultant $\mathcal{R}$ and P parameter surfaces, a result that is not always observed with less parsimonious models. Second, the wider peak in the parameter surfaces for the rainfall–SSflux modelling indicates that the best parameter estimates characterizing the sediment behaviour are less clearly identified in comparison with those for the river flow behaviour. This is probably caused by the greater non-stationarity, i.e. more instances of changing behaviour, within the sediment system.

By undertaking the uncertainty analysis using only one month of rainfall–river flow data (i.e. February 1996), the parameter values that best describe the behaviour are more closely defined (i.e. the peak in figure 8*a* is sharper) in comparison with the year-long data series. This demonstrates that a single month's data fail to capture all of the key behavioural characteristics of even the river generation behaviour, and thereby underlines the importance of intensive monitoring for several months that cover periods of low flow and extreme hydrometeorological events.

The simplified uncertainty estimation procedure presented in this section is, however, overly pessimistic given the parameter estimation procedure being used elsewhere within the paper. The procedure adopted elsewhere within the paper (SRIV) uses only the part of the data spectrum which is relevant to the dynamics of the system being modelled. In other words, the high-frequency components in the rainfall and river flow or SSflux data, that are beyond the dynamic range of the system, are being filtered out during the parameter estimation. The resultant parameter estimates are then better defined.

(d) *Identification of higher behavioural order*

By examining the results of the 'optimal' first-order, rainfall–river flow model applied to a single month's data (i.e. February 1996) within figure 8*b*, it can be seen that the model accurately describes the rising stage and initial and intermediate recession periods. Obviously, the recursive estimation procedures are optimizing the parameters to characterize the periods when most of the water or suspended sediment mass is being discharged. In contrast, the late recessions are consistently poorly characterized, giving some autocorrelation in the model residuals. Poor prediction of part of the recession curve is a well-known phenomenon within river catchment modelling and may indicate the presence of higher-order dynamics within the system.

Second-order models of river generation have been described at least since the work of Horton (1933). Within the Hortonian conceptual model two components make up river response; these relate to the two 'separate' pathways of IOF and subsurface flow. More recently, Hewlett & Hibbert (1967) attributed this bimodal catchment behaviour to the components of subsurface flow and saturation overland flow (SOF) on slopes. The SOF results from a combination of exfiltration of subsurface flow and precipitation falling onto saturated soils.

Other researchers suggest that river generation is better described as a third-order system, where the subsurface component of the Hewlett & Hibbert (1967) model is divided into a 'shallow or fast or soil water pathway' and a 'deep or slow or groundwater pathway'. Evidence for this higher-order system arises from observations of the subsurface system (Chappell & Franks 1996), physically based modelling of chemical data (Robson *et al.* 1992) and DBM modelling (Young *et al.* 1997).

Different flow pathways have different flow regimes and spatial incidences and thereby generate suspended sediment in different ways. For example, the IOF or SOF component would be responsible for mobilizing sediments on haulage road gullies, skid trails and old landslide surfaces, while soil piping, and mass movements on slopes and channel banks may be more associated with the subsurface component. It is clear, however, that such simple associations are difficult, given that water exchanges occur between the two component pathways. Field observation within the Baru catchment indicates an

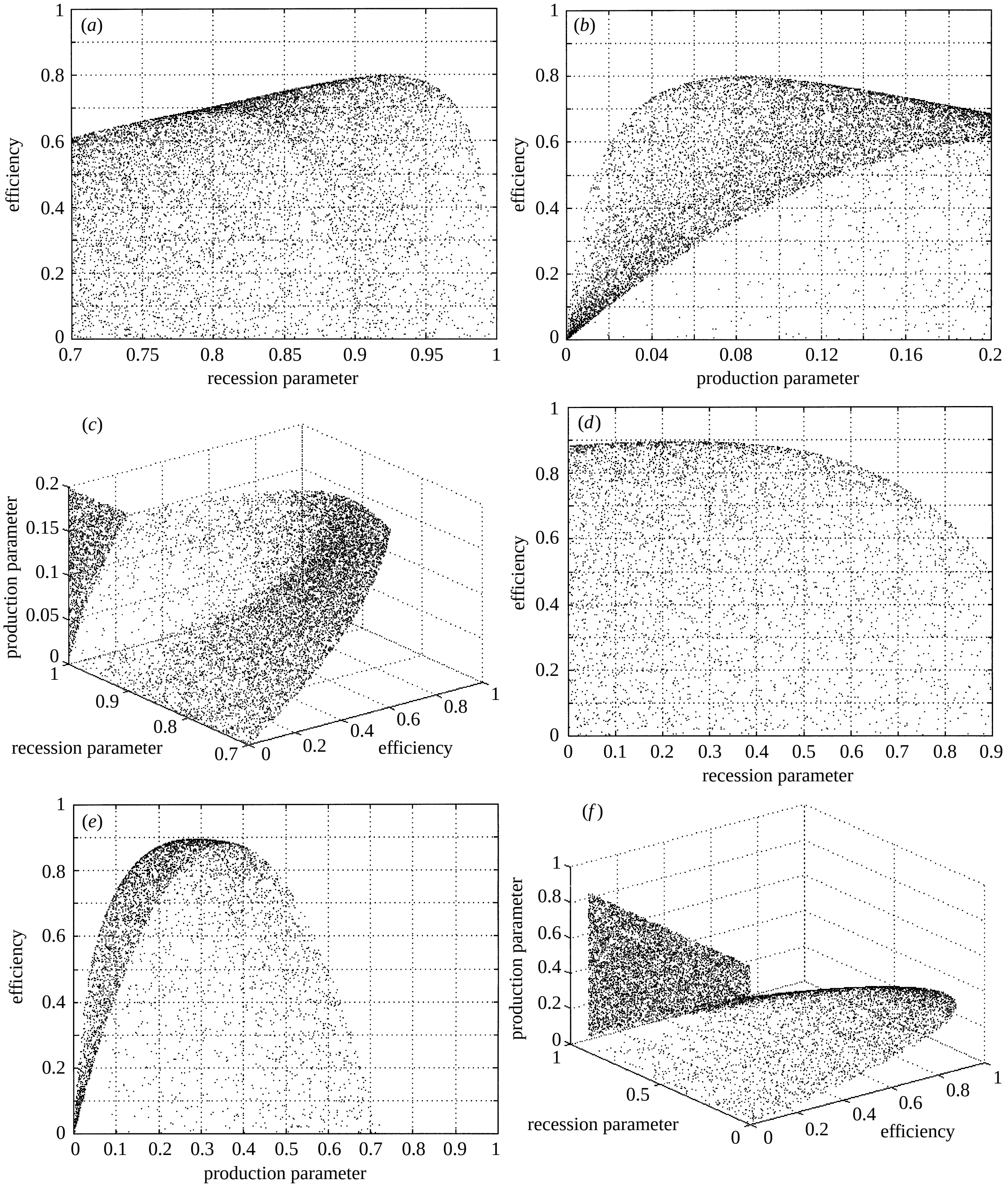

Figure 7. The results of 10 000 Monte Carlo realizations of the first-order, nonlinear TF models given random parameter sampling. (*a–c*) The results of parameter uncertainty on rainfall–river flow model efficiency (ϵ); (*d–f*) the results of parameter uncertainty on rainfall–SSflux model efficiency. The whole data series (i.e. 5 min data for the period 1 July 1995 to 30 June 1996) was used within this uncertainty analysis.

alternative conceptualization of bimodality within the rainfall–SSflux behaviour. Sediments temporarily stored within the channels (following channel or slope erosion) are seen to be mobilized very quickly during the first stages of storm events. In contrast, localized mass wasting triggered by an increase in soil water status or particulate transport from skid trail surfaces to streams may be expected to have greater travel times. Therefore, one might conceptualize the slope and in-channel elements of the catchment as two distinct systems.

Given the physical plausibility of higher-order rainfall–SSflux and rainfall–river flow behaviour, the same

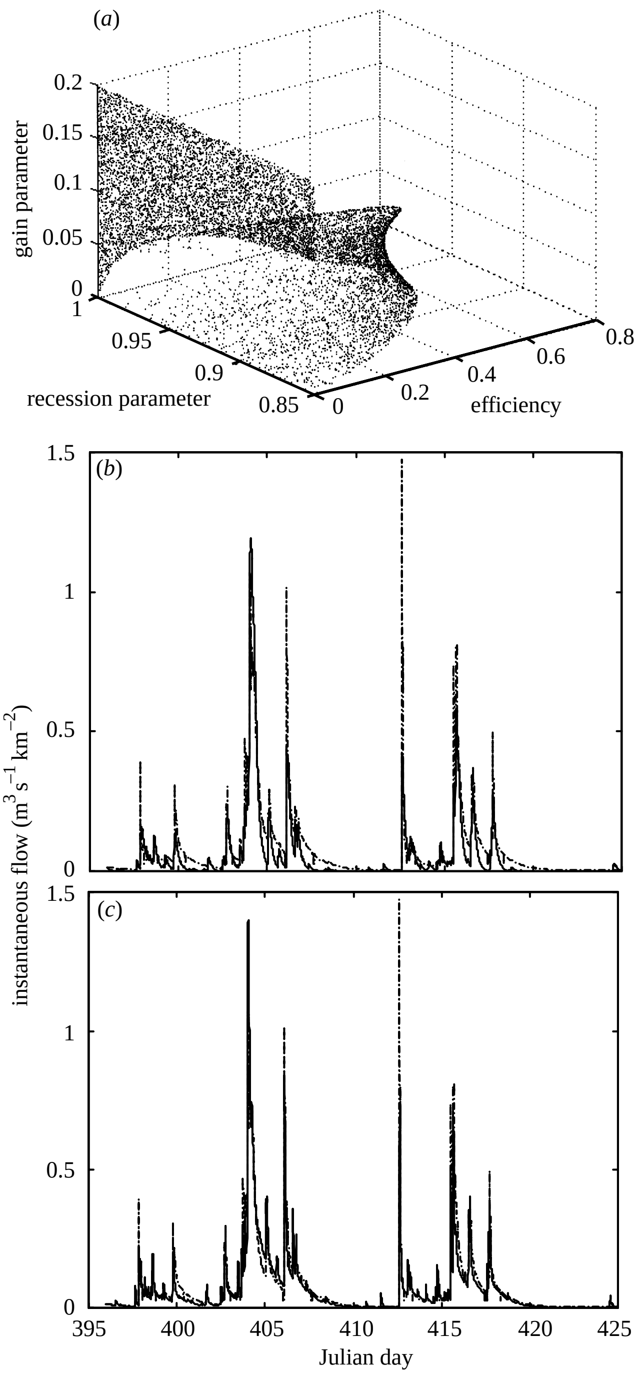

Figure 8. Results of rainfall–river flow modelling of 5 min data collected during the single month of February 1996. (*a*) The parameter uncertainty resulting from the first-order, nonlinear TF model used, (*b*) the river flows predicted (dark, solid line) by the optimum first-order nonlinear TF model against the measured river flows (light, broken line), and (*c*) shows the river flows predicted (dark, solid line) by the optimum second-order nonlinear TF model against the measured river flows (light, broken line). River flows shown on the *y*-ordinate are instantaneous flows (m^3 s^{-1} km^{-2}) recorded on a 5 min basis.

recursive techniques used to estimate the first-order TF were, therefore, used to estimate second- and third-order models. These models can be decomposed into a series of first-order systems acting in parallel. 'Acceptability' of these higher-order models is judged with reference to two objective statistical measures; the first measure being the simplified Nash & Sutcliffe (1970) efficiency measure, ϵ. The second measure used, the Young information criterion, YIC, is more heuristic and effectively identifies whether the estimated model is overparameterized. The measure is defined as

$$\mathrm{YIC} = \log_{\mathrm{e}} \frac{\sigma^2_{\mathrm{error}}}{\sigma^2_{\mathrm{obs}}} + \log_{\mathrm{e}}\{\mathrm{NEVN}\}, \tag{6}$$

where the first term is a measure of the model efficiency and NEVN (normalized error variance norm; see Young & Beven 1994), which combines a measure of parameter uncertainty with the degree of overparameterization. In combination these terms will identify the model which provides the best compromise between model efficiency and parameter uncertainty without overparameterization; this will be indicated by a larger negative YIC value.

Higher-order modelling of the rainfall–river flow during the single month (i.e. February 1996) clearly shows a visible improvement in the prediction of the late recessions (figure 8*c*). Only a small increase in efficiency from 0.819 to 0.864 is produced by using a second-order rather than first-order model; however, the YIC only reduces a little from −11.05 to −10.13 indicating that the model has not become overparameterized, where the data would not justify the model order. Higher-order modelling was next applied to the rainfall–river flow for the whole year. While the efficiency increased by a small amount from 0.8018 (first order) to 0.8024 (second order) to 0.8358 (third order) the YIC fell greatly from −13.04 to −3.42 and −3.86, respectively, indicating that higher-order models could not be justified. Physically based understanding of the catchment behaviour gives some explanation of this phenomena. Recent comparison of field-measured with model-derived hydraulic parameters within study catchments has demonstrated that river generation is dominated by subsurface flow (Sinun *et al.* 1992; Sherlock 1997; Chappell *et al.* 1998*a*) and that this pathway is very complex including the effects of pressure waves, preferential pipe flow and matrix (i.e. advective) flow (Chappell *et al.* 1998*a*). It is, therefore, not implausible that such behaviour is poorly characterized by two or three discrete pathways.

In some contrast, second-order modelling of the rainfall–SSflux behaviour of the whole annual time-series for the Baru catchment indicated a statistically justifiable model. While the efficiency of the sediment generation model only increased very slightly from 0.896 to 0.898, the YIC reduced only slightly from −11.96 to −11.47, indicating that a second-order model is justifiable. In some contrast, the recursive estimation techniques failed to identify a third-order model for the rainfall–SSflux. The second-order TF (again, with no initial delay) that describes the rainfall–SSflux is given as

$$s(k) = \frac{0.2938 - 0.2837z^{-1}}{1 - 11.1730z^{-1} + 0.1971z^{-2}}\, r_{\mathrm{e}}(k), \tag{7}$$

which can be decomposed, by partial fraction expansion, into the two parallel first-order TFs shown in figure 9. The time constant, TC, shown for each of the two parallel

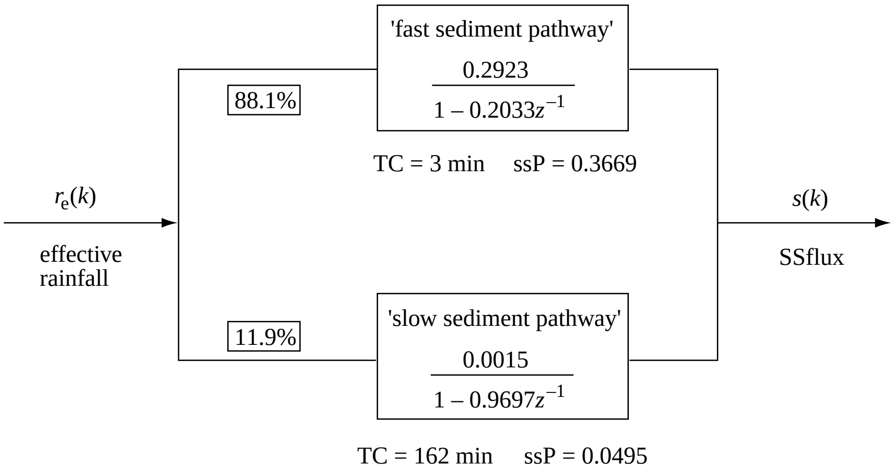

Figure 9. The two parallel, first-order TF models describing rainfall–SSflux behaviour of the whole Baru catchment.

sediment pathways is derived directly from the recession, $\mathcal{R}$, parameter, where

$$\mathrm{TC} = \frac{-t_{\mathrm{base}}}{\log_e(-\mathcal{R})}, \tag{8}$$

and t_{base} is the time base of the sampling (here 5 min). Within rainfall–river flow modelling the TC can be equated with the residence time of the water within the catchment (Young 1992). For rainfall–SSflux modelling the characteristic may be equated with the travel time of particulates moving from the sediment sources to the catchment outlet (i.e. weir). The second additional response characteristic shown within figure 9 is the steady-state production, ssP, which is the steady-state production relative to input, and is calculated from:

$$\mathrm{ssP} = \frac{P}{1+\mathcal{R}}, \tag{9}$$

The proportion of the sum of the ssP for all parallel pathways indicates the proportion of the sediment flux that travels along that particular pathway. Within the second-order model identified, 88% of the suspended sediment appearing at the catchment outlet reaches there very quickly, within about 3 min. An in-channel or near-channel sediment source is, therefore, postulated for this 'fast sediment pathway'. This is consistent with the field observation of large volumes of sediment temporally stored within the channels particularly for 100–200 m upstream of the site 2-east and 2-middle weirs (Douglas *et al.*, this issue). These sediment accummulations were associated with the two landslides within site 2-east and road culvert collapses within the two eastern tributaries of site 2-middle (figure 1). The 'slow sediment pathway' with its travel time of 2 h 43 min may be associated with sediment being transported from sources away from the channels, perhaps from skid trails or haulage roads. Bennett (1974) has suggested that this later pathway can be described by a first-order process. Clearly, such interpretations are tentative, particularly given uncertainties in the partitioning of the ssP (Young 1992) and the risks of oversimplifying a complex system into two discrete pathways, as noted previously. The hypothesis of a bimodal sediment system dominating the behaviour of the whole Baru catchment is, however, something that might be investigated within future field programmes.

(e) *Between-site variation in the recession and production parameters*

The $\mathcal{R}$- (recession) and P- (production) parameters shown within figure 9 and tables 3 and 4 are linear characteristics of the behaviour of the rainfall–river flow and rainfall–SSflux systems observed at the main catchment weir and four subcatchment weirs.

The $\mathcal{R}$-parameter indicates a more 'flashy' system behaviour as the parameter value increases from -1. Here the interpretation describes behaviour at the 'peak of storms' as the parameters are optimized to describe the behaviour of the majority of the SSflux, which occurs during these periods. Comparison of the $\mathcal{R}$-parameter for the rainfall–river flow models (table 3) within those from the rainfall–SSflux models (table 4) indicates that the sediment generation at the peak of storms is generally more flashy than the river generation at the peak of storms. This effect is apparent even after the greater nonlinearity of the rainfall–SSflux system has been captured by the more nonlinear $r_e(k)$ submodel. This indicates that the flow of suspended sediments is rapidly exhausted during storm events. The between-site variation in the $\mathcal{R}$ for the rainfall–river flow models (table 3) appears to be less than the parameter uncertainty (figure 7*a*), given the behavioural characteristics observed in one year's site 1 data. While the parameter uncertainty for the rainfall–SSflux model is larger (figure 7*d*), the between-site variation in the $\mathcal{R}$ is considerably greater. Considering only the behaviour of the basins with a perennial flow regime, the sites with greater annual SSflux per unit area (table 1) exhibit a less flashy sediment behaviour. This is consistent with the concept of those sites generating greater volumes of sediment, notably site 2-east containing the two landslides, being more difficult to rapidly exhaust of sediment during storms (Douglas *et al.*, this issue). The low efficiency for the rainfall–SSflux modelling of site 4($\epsilon = 0.46$), may mean that meaningful interpretation of the $\mathcal{R}$-value for this site is unrealistic. Clearly, any interpretation of the behavioural parameter of $\mathcal{R}$ is as tentative as the ideas relating to model order, though again, such interpretations may stimulate new avenues of field investigation.

The P-parameter defines the production of river flow or SSflux relative to the (normalized effective) rainfall input. This term varies between sites with the same rainfall in direct proportion to the time-averaged production of water or suspended sediment per unit area. Thus, the linear relationships between P and annual run-off depth (mm) or annual SSflux per unit area ($\mathrm{t\,km^{-2}\,yr^{-1}}$) have coefficients of determination (R^2) of 89% and 83%, respectively. By normalizing the production by $1+\mathcal{R}$, to remove the interaction between P and $\mathcal{R}$, the resultant value of ssP is strongly correlated ($R^2 = 90\%$) with both the run-off and SSflux. This means that estimates of the spatial variability in SSflux from contributory areas of a particular scale can be incorporated within uncertain TF modelling by varying the ssP and P.

5. CONCLUSIONS

(a) *Modelling success*

The parsimonious modelling strategy using only three parameters (β, $\mathcal{R}$ and P) can model 80% of the variance in 5 min resolution, annual behaviour of the rainfall–river flow system and 90% of the rainfall–SSflux system of the whole Baru catchment. This success is despite the potential non-stationarity introduced by the occurrence of a 10–20 year return period rainstorm at the middle of the data series. Given the considerable success with such a parsimonious strategy, clear statistical justification must be made before models with greater numbers of parameter types (i.e. higher-order models), that are validated against catchment outputs alone, are used to predict river flow or SSflux. This is particularly important given that some parameter interaction, and hence poor reliability in parameter estimates, is present even within parsimonious modelling.

(b) *Process interpretation*

After taking into account parameter uncertainty, it is clear that the sediment-generation system is considerably more sensitive to the antecedent or catchment conditions (c.f. β-parameters) in comparison with the river flow-generation system and is probably due to the nonlinear relationships between soil particle entrainment and either rainsplash or surface water flow. The degree of the antecedent effects is similar for all of the perennially flowing streams monitored, but was shown to reduce as flows become intermittent due to reduced efflux of subsurface waters. Examination of the $\mathcal{R}$-parameter indicates that the different perennial streams show a similar responsiveness in their river flow behaviour, but show a slower exhaustion of suspended sediments as sediment availability increases. The DBM modelling indicated the possible existence of slightly higher-order (i.e. second-order) dynamics within the rainfall–SSflux. This may be caused by the differential behaviour of in-channel and distal slope sources and is something that might be addressed in future field programmes. Last, the variation in the parameter values that characterize the rainfall–river flow and rainfall–SSflux of the subcatchments of the modelled second-order streams (and possibly first-order streams also) might be used as an estimate of the likely range in river flow and SSflux behaviour of areas of a similar size near to the Baru experimental catchment.

(c) *Ongoing model development*

The DBM model structures identified within this paper are only the first stage in an ongoing modelling programme. The central issue for model development is the identification of more robust techniques for the characterization of the nonlinearities (i.e. the $r_e(k)$ submodel). Such developments include the incorporation of internal state variables of soil moisture, piezometric surface and local denudation rates. Given the level of statistical explanation afforded by the DBM models, with fixed and time-varying parameters, it would be possible to use these approaches to undertake real-time forecasting of water and suspended sediment flows at gauged sites, as described by Lees *et al.* (1994). Further work needs to be undertaken to understand the manner in which the DBM parameters differ between those defined from perennial stream behaviour and those defined from the behaviour of ephemeral streams at the scale of the individual sediment-producing landforms. Equally, the DBM approach should be applied to considerably larger catchment scales (e.g. the nearby 721 km^2 Ulu Segama catchment and the whole 2450 km^2 Segama catchment) where SSflux behaviour may change as channel slope reduces and opportunities for in-channel storage increase. The potential to apply DBM approaches at scales from the headwater landform (0.1 ha) to the region (1000 km^2) may improve understanding of transfer of suspended sediments through the whole river aquatic system from headwaters to estuaries.

(d) *Ongoing model development for forestry scenarios*

The whole Baru catchment could to be modelled as a semi-distributed multiple-input single-output form of the DBM model where the river flow and SSflux from the whole catchment is modelled from the routed outputs of the subcatchment areas (Cluckie 1993). Tentatively, one might suggest that a dominant erosional landform (e.g. road gully, landslide) could be associated with each of the smaller contributory areas of the Baru catchment. The occurrence of each erosional landform within the whole catchment could then be altered by changing the area weight of the model component associated with the particular contributing area associated with that landform. If different forestry operations can be linked to particular erosional landforms (e.g. construction of unsurfaced haulage roads and gully development), then this gives a method of using DBM modelling to examine the possible impact of different forestry operations on the sediment behaviour of the whole Baru catchment. Such an approach could, therefore, form part of detailed assessments of the ecological sustainability of different forestry practices. Clearly, the results of such 'scenario modelling' would be tentative, though it should be remembered that that results of physics-based models should also be considered tentative as internal state data is rarely available for validation of their physical processes descriptions.

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