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Research

Long-term responses of rainforest erosional systems at different spatial scales to selective logging and climatic change

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Long-term (21–30 years) erosional responses of rainforest terrain in the Upper Segama catchment, Sabah, to selective logging are assessed at slope, small and large catchment scales. In the 0.44 km² Baru catchment, slope erosion measurements over 1990–2010 and sediment fingerprinting indicate that sediment sources 21 years after logging in 1989 are mainly road-linked, including fresh landslips and gully erosion of scars and toe deposits of 1994–1996 landslides. Analysis and modelling of 5–15 min stream-suspended sediment and discharge data demonstrate a reduction in storm-sediment response between 1996 and 2009, but not yet to pre-logging levels. An unmixing model using bed-sediment geochemical data indicates that 49 per cent of the 216 t km⁻² a⁻¹ 2009 sediment yield comes from 10 per cent of its area affected by road-linked landslides. Fallout ²¹⁰Pb and ¹³⁷Cs values from a lateral bench core indicate that sedimentation rates in the 721 km² Upper Segama catchment less than doubled with initially highly selective, low-slope logging in the 1980s, but rose 7–13 times when steep terrain was logged in 1992–1993 and 1999–2000. The need to keep steep lands under forest is emphasized if landsliding associated with current and predicted rises in extreme rainstorm magnitude-frequency is to be reduced in scale.

Keywords: erosion; sediment transport; rainforest logging; sediment fingerprinting; radionuclides; data-based mechanistic modelling

1. INTRODUCTION

Although it is well established that rainforest logging results in enhanced slope erosion and catchment sediment yields during and following logging [1,2], less is known about long-term recovery, downstream impacts in larger catchments, and the possible effects of current and predicted future climatic change. These issues constitute the principal foci of this paper, which draws upon evidence from long-term studies in the Segama river basin in eastern Sabah in Malaysian Borneo (figure 1). Previous papers established the complex nature (figure 2) of the erosional response

from 1988 to 2003 for selective logging of the small (0.44 km²) Baru catchment. The recovery was punctuated by extreme events, including a secondary peak in 1994–1997 linked to the biogenic decay of logs in road bridges, culverts and stream debris dams, and a spatial switch in sediment sources to landslides and their scars and deposits along a mid-slope-aligned logging road [3–8]. Against this background, four interlinked questions are addressed. How close are slope erosion rates, sediment yields and responses to rainstorms of the small Baru catchment to pre-logging levels 21 years after a single cycle of selective logging? What is the nature of the response of the large (721 km²) Upper Segama catchment to episodes of upstream rotational selective logging over the last 30 years? What are the likely consequences of predicted changes in climate on erosion and sediment fluxes

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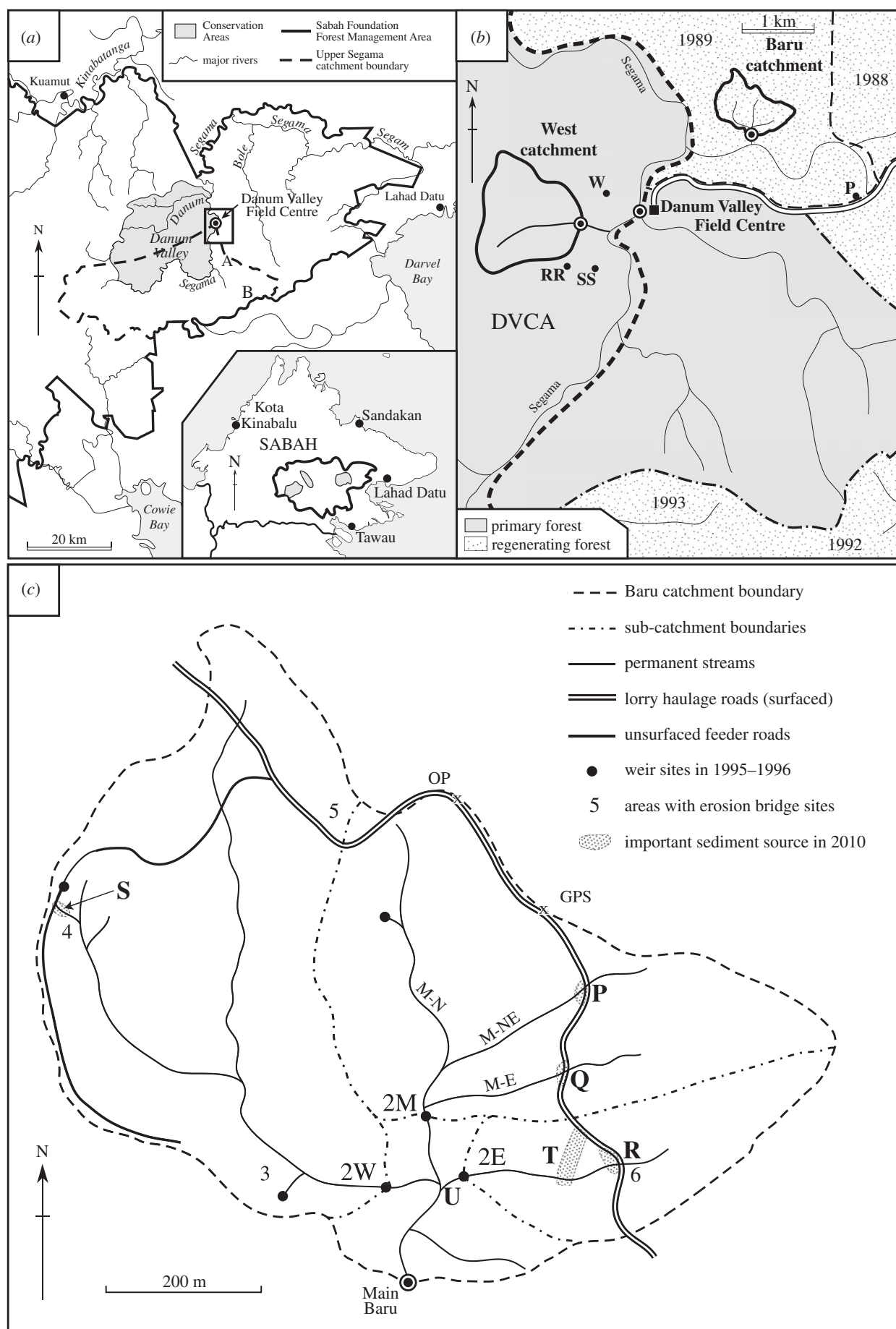


Figure 1. Location maps. (a) The Upper Segama catchment. (b) Location of catchments and erosion bridge sites (W, RR, SS and P) in the Danum area. (c) The Baru catchment. Letters P to U on the map are current sediment source sites mentioned in the text. DVCA, Danum Valley Conservation Area.

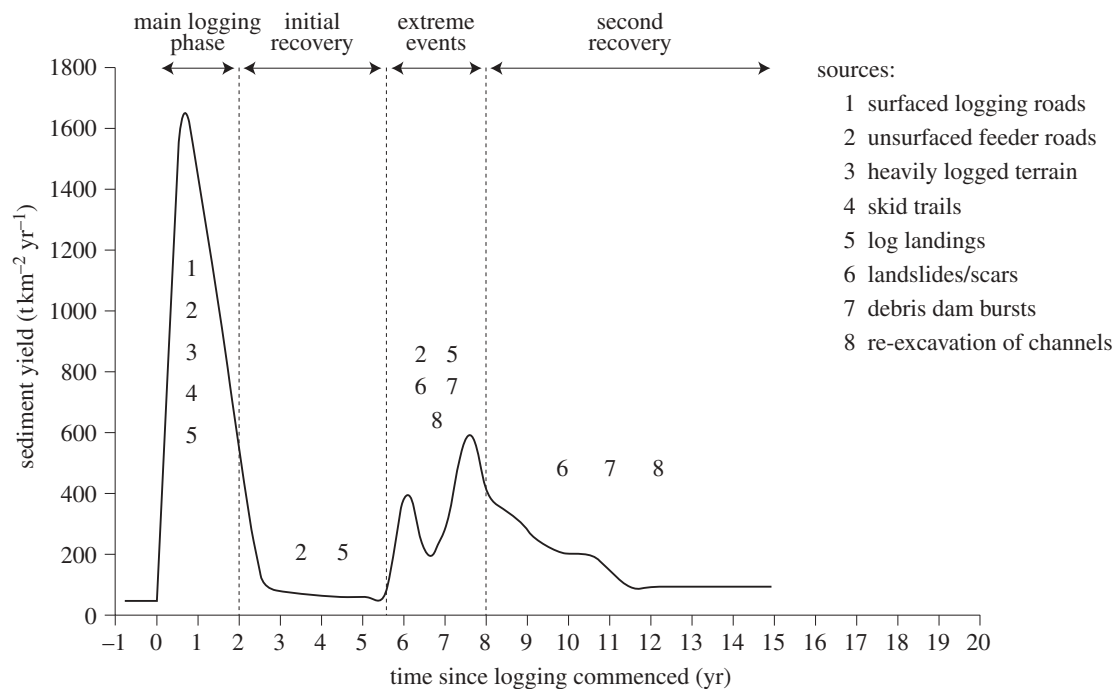


Figure 2. Changes in sediment sources and sediment yield of the Baru catchment since logging commenced in late 1988 (modified after Walsh *et al.* [3]).

across these scales? What messages are there for land management and international policies for reducing impacts of future climatic change? The paper draws upon (i) results of long-term monitoring (over a period of 20–25 years) of slope erosion and river sediment transport, (ii) comparisons of parametrization of suspended sediment/discharge models developed at different stages in catchment recovery using data for 1996 and 2009, (iii) the application of sediment fingerprinting and sediment history approaches, and (iv) evidence for recent climatic change and its effects.

2. STUDY AREA

The study area comprises the forested Upper Segama river catchment in eastern Sabah (figure 1*a*), focusing particularly on the area close to Danum Valley Field Centre (figure 1*b*). The climate of the area recorded at Danum Valley Field Centre daily since mid-1985 (table 1) is equatorial, but with seasonal wind changes brought about by the Indo-Australian Monsoon System. The northeast monsoon from November to March and the southwest monsoon from June to August are separated by transitional periods in April–May and September–October. Mean annual temperature is 26.9°C with an annual range of 1.7°C. The mean annual rainfall is 2849 mm (s.d. 451 mm), with monthly means ranging from 315 mm in January to 156 mm in April. Daily rainfalls of 50 mm or greater occur on average 9.0 times per annum. Of the 22 daily rainfalls exceeding 100 mm in the period 1985–2010, 14 occurred in December, January and February. The highest recorded daily falls are 182.2 mm (9 February 2006), 177.2 mm (27 March 1988) and 162.5 mm (19 January 1996).

The geology of the Upper Segama is complex. The Miocene Kuamut Formation (a melange of slumped sedimentary and volcanic rocks with interbedded sandstones, mudstones and tuffs, known collectively

as slump breccia) is dominant close to Danum, but older Chert–Spilite formation and metamorphic and igneous gabbro, diorite and granite rocks of the Lower Triassic Crystalline Basement are prevalent in the mountainous headwaters [9]. Altitude varies from approximately 100–1200 m.a.s.l. Slope angles close to Danum are generally 10–30° but are 30–50° on the higher hills and in the Segama headwaters. The topography is finely dissected with a drainage density of 20–22 km km⁻² [3]. Soils are mostly USDA (United States Department of Agriculture) Ultisols. In the Baru and West catchments, loams and silt-loams are dominant [10], but sandy loams are characteristic of steeper slope sites in the primary forest [8]. Soils are generally at least 1.5 m deep and often much deeper.

Apart from the primary lowland dipterocarp forest of Danum Valley Conservation Area and the Palum Tambun catchment immediately south of the Field Centre and some montane forest in the higher mountains, the area comprises regenerating forest that has been rotationally selectively logged in annual coupes since the early 1980s. Commercial tractor and high-lead logging techniques have been generally used, with a combination of the two employed when the Baru catchment was logged in 1988–1989, but Reduced Impact Logging (RIL) protocols were employed experimentally in part of the 1992–1993 coupes [11] and have since been adopted as policy. The history of logging and land-use change within the area, together with the logging practices, is covered in more detail by Reynolds *et al.* [12].

3. METHODS

(a) Measurement of slope erosion

Long-term changes in slope erosion rate and at channel cross-sections are assessed mainly using the

Table 1. Climatic statistics for Danum Valley Field Centre 1985–2010.

climatic element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
mean temperature (°C)	26.0	26.1	26.8	27.7	27.7	27.3	27.0	27.0	27.1	27.0	26.9	26.5	26.9
mean rainfall (mm)	315	233	207	156	260	231	203	188	219	294	261	282	2849
s.d. of rainfall (mm)	127	154	116	105	118	92	67	69	96	103	90	118	451
months with <100 mm rain	1	3	7	8	2	2	1	4	1	0	0	0	1.2
days with ≥ 50 mm	1.4	0.8	0.4	0.5	0.9	0.8	0.6	0.4	0.4	1.0	1.0	0.9	9.0
maximum recorded in a day (mm)	162.5	182.2	177.2	122.5	95.2	109.4	115.6	77.1	124.3	114.0	116.0	119.5	182.2

repeat-measurement erosion bridge technique [8,13]. Depending on the erosion bridge used, each transect site assesses ground-level change at 29–37 points across terrain between two stakes 1–3 m apart driven into the ground surface. A network of 58 sites (29 in primary forest, 29 in regenerating forest selectively logged in 1988–1989) was installed in June 1990, supplemented by 36 new sites in the logged area in 1994–1995 and 70 sites (48 in primary forest; 22 in logged forest) in 1998–1999. Transects were remeasured generally at yearly intervals. Around 100 sites were still operational in 2010; some sites were lost through uprooting or breakage of stakes by animals, rotting of non-aluminium stakes, and burial by landslides. In primary forest, sites are located at three locations in the Danum Valley Conservation Area (figure 1*b*) covering a range of slope angles. In the logged area (figure 1*b,c*), attention focuses on elements of the post-logging terrain mosaic, notably: unsurfaced logging roads; skid trails; log-landings and other heavily disturbed terrain; lightly logged slopes; landslide scars; and channel cross-sections. The data obtained are used here to assess trends in ground-level change between four 5 year sections of the 20 year period 1990–2010.

(b) Measurement of rainfall, catchment flows and suspended sediment

Daily rainfall totals and rainfall intensities have been recorded at Danum Valley Field Centre since August 1985 using a standard rainfall gauge and a Casella natural siphon autographic gauge, respectively. In the Baru catchment, tipping-bucket rainfall gauges linked to data loggers have provided additional information. Streamflow (via calibrated stage monitoring) and suspended sediment concentration (SSC) have been measured at the selectively logged Baru catchment and the primary forest West (W8S5) catchment since mid-1988 and at the Segama at Danum since 1985 (figure 1). Early instrumentation is described by Douglas *et al.* [4]. In July 1995, these observations were complemented by turbidity monitoring at 10 s intervals using a Partech IR15C probe, where data were typically integrated over 5 min periods for further analysis [6,7]. In 2003, the catchment network was equipped with Campbell data-logging systems, with Analite-195 turbidity sensors (with integral wipers), conductivity/temperature probes and pressure transducers providing 1 min data integrated to 15 min intervals on turbidity, conductivity, water temperature

and river stage. The equation $SSC \text{ (mg l}^{-1}\text{)} = 0.6714 T$ (nephelometric turbidity units, NTUs), obtained by analysing representative water samples for SSC using the gravimetric method, is used to convert turbidity to SSC. The data generated are used to assess and model changes in suspended sediment characteristics and dynamics through post-logging time.

(c) Data-based mechanistic modelling of stream sediment dynamics

A data-based mechanistic (DBM) modelling approach was used to assess changes in the dynamics of the suspended sediment system of the small Baru catchment between 6.5 and 19.5 years after selective logging ceased in June 1989. The first period lies in the secondary pulse of sediment immediately following the *ca* 8 year return period rainstorm of 19 January 1996 (177 mm in the Baru; 162.5 mm at Danum Valley Field Centre), where the event resulted in a major debris flow and nine smaller road-linked landslides in the east of the catchment (figure 1*c*), debris dam bursts and very high sediment loads [3,6]. The DBM modelling seeks to assess objectively the degree of recovery in the sediment load–discharge relationship between this first period and 13 years later. (The lack of sufficiently high-resolution turbidity data prior to 1995 precluded modelling of, and comparisons with, pre- and early post-logging times.)

DBM modelling methodology is essentially an interactive process of model development and evaluation and in this study involved the following steps:

- *Selection* of periods with very high quality discharge and suspended sediment load data. Twelve days of 5 min resolution records in February 1996 and 26 days in April 1996 were selected from the period 6.5 years post-logging; 11 days of 15 min records in January 2009 and 30 days in March 2009 were selected to represent the period 19.5 years post-logging. High temporal resolution of the data is essential because of the very flashy nature of suspended sediment responses of tropical streams.
- *Identification* of a range of DBM model structures that describe relationships between suspended sediment load and discharge time-series. With the DBM philosophy, no assumptions are made about the physical processes prior to modelling. Instead, a wide range of dynamic relationships between the output time-series (suspended

sediment load) and potential controlling time-series (stream discharge) are applied. Transfer functions are one of the commonly used mathematical tools to describe these relationships, but other methods are also used.

- *Evaluation* of the performance of the resultant models using a range of statistical tools and objective criteria [14].
- *Rejection* of model structures that either have a low simulation efficiency or involve too many parameters (which would make the models highly uncertain). Most models are rejected at this stage.
- *Acceptance* of the model structure(s) that is appropriate for all periods and also lends itself to a physical interpretation.
- *Derivation of the dynamic response characteristics (DRCs)* from the model parameters, including estimation of the uncertainty in these by Monte Carlo sampling of 1000 values of the parameters.
- *Assessment and interpretation* of the differences in DRCs obtained when the model is applied to each period.

(d) *Sediment fingerprinting and sedimentation history techniques*

Sediment fingerprinting, which is based on comparisons of sediment properties of downstream transported material with hypothesized upstream sources [15,16], potentially allows one to quantify current (using surface fine-sediment in channels) and/or past (using sediment cores) sources. Hypothesized sources, which may be categorized either spatially (e.g. from different sub-catchments) and/or vertically (e.g. surface, shallow subsurface, deep subsurface material and linked to different processes), must have sediment properties that make them distinguishable from each other. Using a combination of sediment properties makes this easier and such a 'multi-proxy sediment fingerprinting' approach is adopted in this paper. An unmixing model can then be used to quantify the relative contributions of sources [16]. Here, some initial results are presented from a survey of current fine bed-sediment at the Baru catchment outlet in relation to upstream tributary bed-sediment and slope source material. After air-drying and sieving, a portable Niton XRF elemental analyser was used to obtain the elemental composition of the less than 63 μm fraction of these samples, representative of the suspended sediment. Although soil aggregates were broken up, care was taken not to crush stone or to grind the samples.

The impact of catchment disturbance on sediment flux is generally reflected in changes in accretion rates of catchment sediment stores, where rates can be determined by radiometric dating using fallout or excess of ^{210}Pb and ^{137}Cs [17]. Sediment cores from floodplain deposits [18–20] and/or lateral channel benches [21] can be used. This study uses the latter approach, as it provides a record from a wider range of high flows than a floodplain site, to explore the history of effects of logging on sediment fluxes for the large (721 km²) Upper Segama catchment. The lateral bench sampled is situated about 6 m above the baseflow river level

and 30 m downstream of the suspension bridge at Danum Valley Field Centre (figure 1). A 0.6 m long and 10 cm diameter core was collected and sectioned into 1 cm slices. Each slice was air-dried and homogenized prior to measurement by gamma spectrometry [17]. Activity concentrations of the target radionuclides (^{210}Pb , ^{226}Ra via ^{214}Pb and ^{137}Cs) were measured using a low background EG&G Ortec HPGe gamma spectrometry system at the University of Plymouth Consolidated Radioisotope Facility.

The Constant Rate of Supply model was used to derive an age–depth model for the core and accretion rates following procedures described by Appleby [17], where it is assumed that excess ^{210}Pb supply from upstream sediment sources is small in comparison with atmospheric fallout. Because of the incomplete fallout ^{210}Pb profile (see later), the fallout ^{210}Pb inventory at depths below the peak ^{137}Cs activity concentration (assumed to be the 1963 peak in weapon-related fallout) was estimated iteratively against the ^{137}Cs marker.

(e) *Mapping of landslide density and distribution*

Landslides were mapped using photogrammetry and GIS techniques for a 225 km² area of the Upper Segama catchment around Danum Valley Field Centre covered by vertical aerial photographs of 1995. The area encompassed terrain of contrasting steepness and covered either by primary forest or regenerating forest that had been logged at different times from 1981 to 1993. It included adjacent areas of similarly steep terrain that were selectively logged in 1992 using commercial logging techniques and RIL protocols and left as undisturbed forest. The individual landslide data were aggregated to yield the number and density of landslides for the different parts of the studied area [22].

(f) *Climatic records and analysis*

Recent and historical changes in the frequency of large rainfall events were assessed by analysing the 100 year daily rainfall series at Sandakan, Kota Kinabalu and Tawau (1910–2009) as well as the shorter record at Danum Valley itself (1985–2009). The computerized records of the Malaysian Meteorological Department from 1960 were extended back in time by using daily rainfall data printed each month in issues of the *North Borneo Herald* from 1906 to 1940 (held at the National Archive at Kew, London) and post-World War II manuscript data found in a storeroom at Kota Kinabalu Airport.

4. SEDIMENT RESPONSE TO SELECTIVE LOGGING AT THE SLOPE AND SMALL-CATCHMENT SCALES: THE BARU CATCHMENT 1988–2010

(a) *Slope-scale evidence: erosion bridge transects and 2010 field observations*

Data from erosion bridge sites for different terrain elements of the post-logging mosaic and for undisturbed primary forest for 5 year periods from 1990–1995 to 2005–2010 (table 2) confirm earlier research

Table 2. Summary of ground lowering rates (mm a^{-1}) at erosion bridge sites on different terrain elements of the Baru catchment (selectively logged in 1988–1989) and adjacent primary forest for 5 year periods from 1990 to 2010. Positive values indicate ground lowering (through erosion or soil compaction). Negative values indicate ground-level rise (through deposition or soil expansion). The numbers of transect sites and measurement points are given in *italics*. n.d., no data.

terrain element	1990–1995		1995–2000		2000–2005		2005–2010	
	mean	<i>sites–points</i>	mean	<i>sites–points</i>	mean	<i>sites–points</i>	mean	<i>sites–points</i>
skid trails	12.92	<i>3–90</i>	0.45	<i>5–155</i>	–3.09	<i>4–128</i>	–5.20	<i>2–74</i>
unsurfaced roads	62.22	<i>6–162</i>	2.47	<i>10–270</i>	5.19	<i>6–162</i>	15.78	<i>5–135</i>
heavily disturbed $<25^\circ$	6.04	<i>11–132</i>	–9.03	<i>19–468</i>	–3.59	<i>18–441</i>	0.70	<i>11–267</i>
heavily disturbed $>25^\circ$	n.d.	n.d.	1.01	<i>10–270</i>	–0.13	<i>9–243</i>	–0.17	<i>7–189</i>
lightly disturbed	n.d.	n.d.	1.41	<i>4–108</i>	1.37	<i>2–54</i>	3.04	<i>2–54</i>
landslide scars	n.d.	n.d.	32.30	<i>3–76</i>	53.80	<i>2–51</i>	86.60	<i>2–51</i>
primary forest $<25^\circ$	0.48	<i>10–370</i>	0.44	<i>10–370</i>	0.70	<i>14–478</i>	–0.11	<i>14–478</i>
primary forest $>25^\circ$	0.16	<i>3–111</i>	0.46	<i>3–111</i>	1.39	<i>13–381</i>	0.56	<i>13–381</i>

Table 3. Changes in suspended sediment responses of the Baru catchment 6–20 years after selective logging ceased in June 1989. SSC, suspended sediment concentration. The year 1995–1996 was July 1995–June 1996.

year	annual rainfall (mm)	rain days >50 mm	storms with peak SSC			hours per annum SSC $> 200 \text{ mg l}^{-1}$
			>500	>1000	$>4000 \text{ mg l}^{-1}$	
1995–1996	3598	10	30	14	6	162.2
2003	3539	17	17	10	2	43.3
2004	3006	8	5	2	1	19.5
2005	2350	5	3	0	0	10.5
2009	3421	11	20	7	0	62.8

[3,5,8] showing that initially high rates of erosion on bare ground sites (skid trails, rutted unsurfaced roads and heavily disturbed terrain) fell rapidly with revegetation. After late 1994, the foci of erosion switched to road-linked landslides and their scars and knickpoints along road drainage gullies. This remains the case, with erosion rates in 2005–2010 only being greatly in excess of primary forest values at landslide scar and unsurfaced road sites, where average ground lowering rates were 86.6 and 15.8 mm a^{-1} , respectively. The temporal pattern at low-angle heavily disturbed terrain sites (mostly heavily compacted log-landing sites) is of interest, with initially high ground lowering rates (6.0 mm a^{-1}) becoming ground-level rises in 1995–2005, but with renewed lowering since 2005. Field observations suggest that this pattern may be related to vegetation. Ground-level rise was recorded when the vegetation comprised a progressively denser *ground* cover, which protected against splash and slopewash and favoured soil expansion via root development. In the last 5 years, however, vertical growth of the vegetation canopy (1.5–2 m high by 2010) has left more bare ground beneath it, possibly accounting for the increased erosion and return to net ground lowering.

Field observations and measurements in summer 2010 indicate the continued importance of erosional activity linked to the mid-slope section of the main logging road (figure 1c), which was constructed as with the whole road system at the time of logging in 1988–1989. Eroding sites include: a fresh landslip at P; an eroding, collapsing road culvert at Q; continued

active gullying of the scar of the 1994 landslide at R (where the gully has deepened by an additional 50 cm in 2005–2010); and further headward erosion, deepening and widening of what is now an 8 m long, 3 m deep, ephemeral waterfall/gorge section at S cut by runoff from an unsurfaced logging road as it cascades down the road embankment towards the pre-existing stream network. There is also active dissection by the 2E Tributary of toe deposits of the 1996 landslide at T. In contrast to earlier post-logging time from 1989 to 2005 [3,23], tributary streams in 2010 were characterized by fewer debris dams and the confluence region at U was free of logging debris and accessible for the first time since logging.

(b) *Catchment-integrated evidence: I. suspended sediment responses in storm events*

Data at the Main Baru station for 2003–2005 (table 3) indicate a further decline in the size and duration of suspended sediment responses compared with in 1995–1996 during the secondary peak in erosion. Despite similar annual rainfall, all SSC parameters were lower in 2003, despite its greater number of large rainstorms, than in 1995–1996. Responses in 2004 and 2005 were much lower still, reflecting the lower annual rainfalls and reduced large-storm frequencies of those years. Suspended sediment responses in the wet year of 2009, however, differed little from those of 2003 and the suspended sediment yield rose to $215.5 \text{ t km}^{-2} \text{ a}^{-1}$, compared with $277.5 \text{ t km}^{-2} \text{ a}^{-1}$ in 2003 and $592.5 \text{ t km}^{-2} \text{ a}^{-1}$ in 1995–1996.

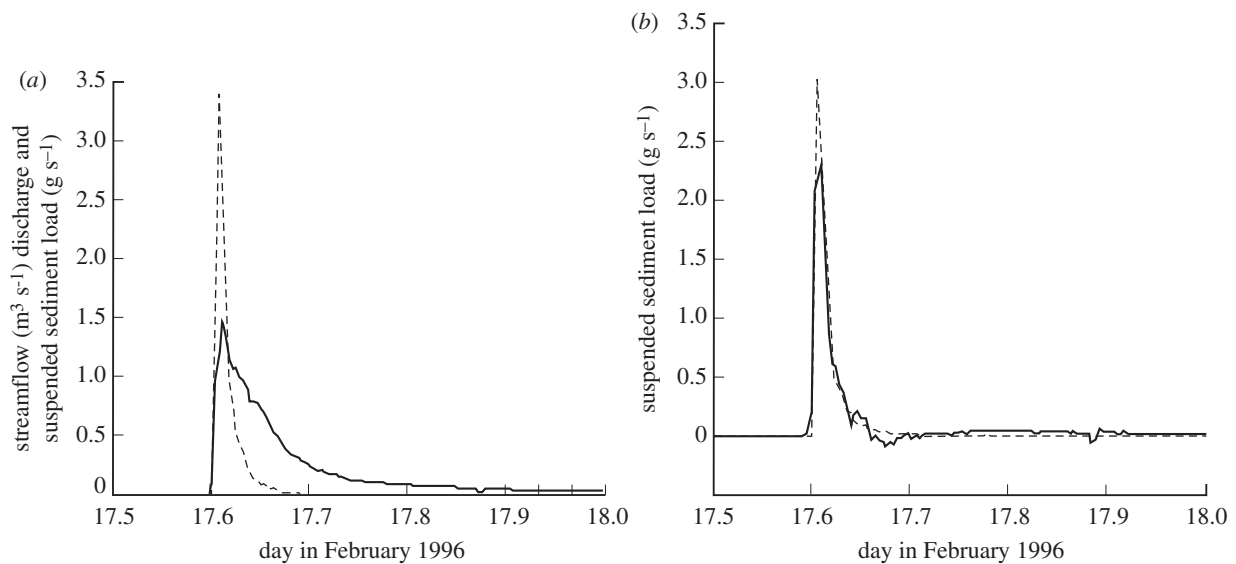


Figure 3. Example responses of the 0.44 km² Baru catchment for a 12 h period covering a storm event on 17 February 1996. (a) Monitored streamflow (solid line) and monitored suspended sediment load (dashed line). (b) Comparison of suspended sediment load simulated with a DBM continuous time model (solid line) with the monitored record (dashed line).

(c) Catchment-integrated evidence: II. modelling dynamics of sediment load

The DBM modelling approach provided a more objective way of assessing the change in suspended sediment dynamics (and degree of recovery) of the Baru catchment between 1995–1996 and 2009 than achieved in §4a. The model identification procedures generated a range of model structures relating Baru discharge and suspended sediment load. The most appropriate relationship was found to be a dynamic model that uses both the rate of change of discharge and inertia in the relation and needs to identify only three parameters to capture the short-term dynamics of the relationship. It uses an algorithm based on a continuous-time transfer function that takes the form,

$$\frac{dy}{dt} = -ay_{(t)} + b_1 \frac{dq_{(t)}}{dt} + b_2 q_{(t)},$$

where dy/dt is the rate of change of suspended sediment load (kg (5 min)^{-2} or kg (15 min)^{-2}); $y_{(t)}$ is the suspended sediment load (kg (5 min)^{-1} or kg (15 min)^{-1}) at time t ; $q_{(t)}$ is the discharge ($\text{litres (5 min)}^{-1}$ or $\text{litres (15 min)}^{-1}$) at time t ; and a , b_1 and b_2 are the model parameters. Parameter a captures the inertia of the system; parameter b_1 captures the sensitivity of sediment load to the *rate of change of discharge*; and parameter b_2 captures the sensitivity of sediment load to the *value of discharge*. The model structure was identified as the most appropriate using standard DBM model selection criteria. In this case both Young's Identification Criterion and the multiple correlation coefficient (R_t^2 , equivalent to the simplified Nash–Sutcliffe Efficiency measure) pointed to this particular model structure. The model parameters (a , b_1 , b_2) were estimated using the Refined Instrumental Variable method for continuous-time transfer function models [14] as implemented in the Captain Toolbox for MATLAB [24].

This model presented as a transfer function is of the form:

$$y(s) = \frac{b_1 s + b_2}{s + a} q(s),$$

where s is the Laplace derivative operator [25]. The model structure allows the derivation of two key DRCs of the system's behaviour. First, the time constant of the inertia in the discharge to load system (hours) is then given as,

$$\text{TC} = \frac{1}{a}$$

and second, the differencing time constant (in hours; related to the rate of change of sediment load in response to the rate of change of discharge) is given as,

$$T_d = \frac{b_1}{b_2}.$$

This T_d parameter defines the linearized balance between the influence of discharge and its time derivative on sediment load. This describes or captures the dynamics reflected in typical clockwise hysteresis loops between discharge and suspended sediment load.

The model was applied to the storm event of 17 February 1996 (figure 3) and to three other sequences of storm events (covering 11–30 days) within the January–April 1996 and January–April 2009 periods (table 4). As the model incorporated the derivative of discharge to predict suspended sediment load, it magnifies any errors in the discharge data and adversely influences model parameter estimates. This fact reinforces the need to select only periods with the highest quality data. The R_t^2 value obtained for the February 1996 event was 0.93 and similarly high efficiencies were obtained for all the sequences examined. Given the small residuals obtained (figure 3), only slightly improved efficiencies would be obtained by developing a nonlinear model and thus, from the objective of parsimony (minimizing the number of

Table 4. Dynamic Response Characteristics (DRCs) of the continuous-time transfer function models between streamflow and suspended sediment load for the Baru catchment in 1996 and 2009. TC is the time constant of the inertial component, T_d is the differencing time constant, SSG is the steady-state gain of the model (i.e. b_2/a), and R_t^2 is the model efficiency. Standard deviations (s.d.) are given in brackets.

period	TC (s.d.) (h)	T_d (s.d.) (h)	SSG (s.d.) (h)	R_t^2
seven years after logging during secondary peak in erosion following extreme event (with road-linked landslides and debris dam bursts) of 19 Jan 1996 (5 min data)				
12 h in Feb 1996	0.25 (0.01)	1.30 (0.11)	0.44 (0.03)	0.93
26 days in Apr 1996	0.86 (0.02)	1.90 (0.03)	0.04 (0.002)	0.93
twenty-one years after logging (15 min data)				
11 days in Jan 2009	0.17 (0.004)	0.43 (0.01)	0.43 (0.005)	0.89
30 days in Mar 2009	0.42 (0.01)	0.95 (0.02)	0.42 (0.01)	0.95

parameters in order to reduce predictive uncertainty), it was decided to keep to the linear model. The uncertainty about the TC and T_d parameter estimates was then quantified using Monte Carlo sampling of 1000 random values from within the standard deviation of the mean values of parameters a , b_1 and b_2 .

Although the inertia-related time constants (TC) do not differ consistently between 1996 and 2009, values of the differencing time constant (T_d) are consistently smaller in 2009 than in 1996. This implies that the rate of rise in suspended sediment load (and by implication SSCs) with increasing discharge in rising limbs of storm events was measurably reduced in 2009 compared with that in 1996. The larger spread of T_d values for the February 1996 period (figure 4) is to be expected given the much shorter period of data (12 h) used in parameter estimation than in March 2009 (30 days). The modelling approach therefore confirms, but more objectively than in table 3, that catchment recovery is measurably more advanced in 2009 than it was in 1996.

(d) Catchment-integrated evidence: III. sediment fingerprinting evidence

Sediment fingerprinting data of stream fine (less than 63 μm) bed-sediment above and below stream confluences gives additional independent evidence on the relative importance of erosion from different parts of the Baru catchment. The elemental composition of the fine bed-sediment of the Middle Tributary is closer to that of the Middle Northeast than those of the other two headwater tributaries (table 5 and figure 1c). This suggests that most of the suspended sediment is currently being derived from the fresh landslide contained within that sub-catchment (Site P in figure 1c). Calculations using an unmixing model confirm this, indicating that the Middle Northeast Tributary is contributing $69 \pm 3\%$, the Middle East $30 \pm 3\%$ and the Middle North just $1 \pm 1\%$ of the Middle stream's load.

When considering the relative contributions made by the three main sub-catchments (2W, 2M and 2E) to the suspended sediment load of the Baru (table 6), some of the elemental characteristics of the 2E sub-catchment fine bed-sediment are in contrast to those of 2M and 2W, with Zr being much higher and Sr, Zn, Mn and Fe being much lower. Sub-

catchments 2M and 2W are less well differentiated, with the exception of Cu and to a lesser extent Zn. Overall the data suggest a disproportionately high percentage of the current Baru suspended load is derived from the relatively small East sub-catchment. Calculations using the unmixing model indicate that the West, Middle and East sub-catchments, respectively, contribute $45 \pm 2\%$, $6 \pm 4\%$ and $49 \pm 3\%$ of the current Baru catchment load ($215.5 \text{ t km}^{-2} \text{ a}^{-1}$ in 2009). Allowing for different sub-catchment areas, these translate into rates of erosion of 193, 34 and $869 \text{ t km}^{-2} \text{ a}^{-1}$, respectively. These compare with 361, 685 and $1467 \text{ t km}^{-2} \text{ a}^{-1}$, respectively, in 1995–1996, when the sediment loads of the three sub-catchments were measured at instrumented weirs. The high 1995–1996 sediment yield was linked to the 2E sub-catchment being the most affected by road-linked landslides in November 1994 and the extreme storm event in January 1996 [5,6]. This suggests that the 1994 landslide scar at R and toe deposits of the 1996 landslide at T in the 2E sub-catchment (figure 1c) still constitute major sediment sources.

5. SEDIMENT RESPONSE TO SELECTIVE LOGGING AT THE LARGE CATCHMENT SCALE: THE UPPER SEGAMA 1980–2010

(a) The sedimentation record of the Segama river at Danum using fallout ^{137}Cs and ^{210}Pb

Activity concentrations of fallout ^{210}Pb in the lateral bench core of the Segama at Danum (figure 5a) are low relative to the higher concentrations found in mid-latitudes [26]. Assuming that the input of fallout ^{210}Pb from deposited sediment is low relative to direct fallout, low activity concentrations can be linked to higher rates of sedimentation. The marked troughs in the middle and upper sections of the profile (figure 5a) thus imply marked dilution of activity concentration by periods of enhanced rates of sediment accretion.

Caesium-137 activity concentrations (figure 5b) are also very low and below detection limits in much of the core in line with reportedly low levels of radioactive fallout in equatorial regions following weapons testing [27]. Much higher activity concentrations of ^{137}Cs were measured at mass depths of 49–54 kg m^{-2} and the peak (at a mass depth of 52 kg m^{-2}) is inferred

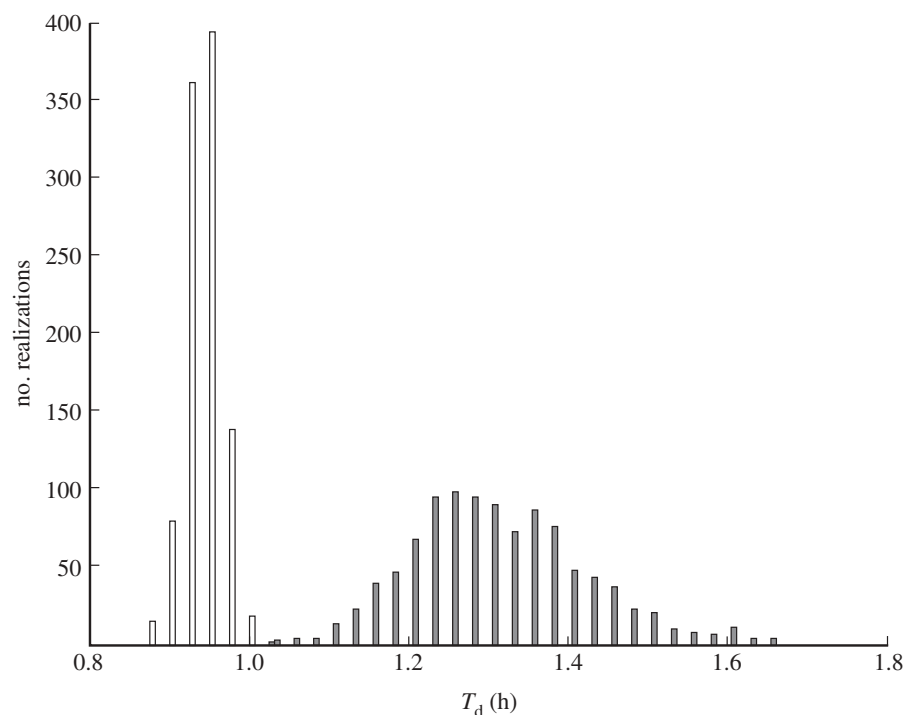


Figure 4. Distribution of differencing time constant (T_d) for the 12 h period in February 1996 (grey bars) together with the 30 day period of March 2009 (white bars) based on Monte Carlo simulation of 1000 values of model parameters a , b_1 and b_2 with their estimated covariance matrix for a continuous-time transfer function model of suspended sediment load for the Baru catchment.

Table 5. Elemental analysis (ppm) of the fine ($<63\ \mu\text{m}$) fraction of bed-sediment samples taken in June 2010 for the Middle (2M) Tributary of the Baru and its three upstream source streams. For locations see figure 1c.

stream/tributary	Zr		As		Ni		Mn	
	ppm	2σ	ppm	2σ	ppm	2σ	ppm	2σ
Middle North	314	6	22	3	101	27	889	58
Middle Northeast (2009 landslide)	666	8	15	3	<36	n.a.	300	38
Middle East (collapsed culvert)	466	7	9	3	<35	n.a.	131	31
Middle Tributary d/s of weir	602	8	15	3	<36	n.a.	329	40

Table 6. Elemental analysis (ppm) of the fine ($<63\ \mu\text{m}$) fraction of bed-sediment samples taken in June 2010 for the Baru stream and its principal tributaries. For locations see figure 1c.

stream	area (km^2)	Zr		Sr		Zn		Cu		Mn		Fe	
		ppm	2σ	ppm	2σ	ppm	2σ	ppm	2σ	ppm	2σ	ppm	2σ
2 West	0.190	606	7	42	2	50	7	28	10	326	39	23 204	189
2 Middle	0.143	602	8	40	2	42	7	<14	n.a.	329	40	22 123	189
2 East	0.046	756	8	31	2	25	6	19	9	110	30	14 746	152
Main Baru	0.441	712	8	35	2	30	6	22	9	250	36	19 271	172

to mark the 1963 peak in nuclear bomb testing and associated fallout prior to the implementation of the Test Ban Treaty on 10 October of that year. The inferred 1963 date permitted the fallout ^{210}Pb curve (figure 5a) to be recalibrated (and inverted) to yield a tentative graph of sedimentation rate from *ca* 1960 to 2007 (figure 5c). The temporal pattern of peaks and troughs points to a modest rise in sedimentation

rate in the early 1980s, an intermediate peak in the early 1990s and a marked peak around 2000.

(b) *Logging history, landslide occurrence and land management in the Upper Segama*

The temporal pattern of sedimentation (figure 5c) fits with the known history of logging in the Upper

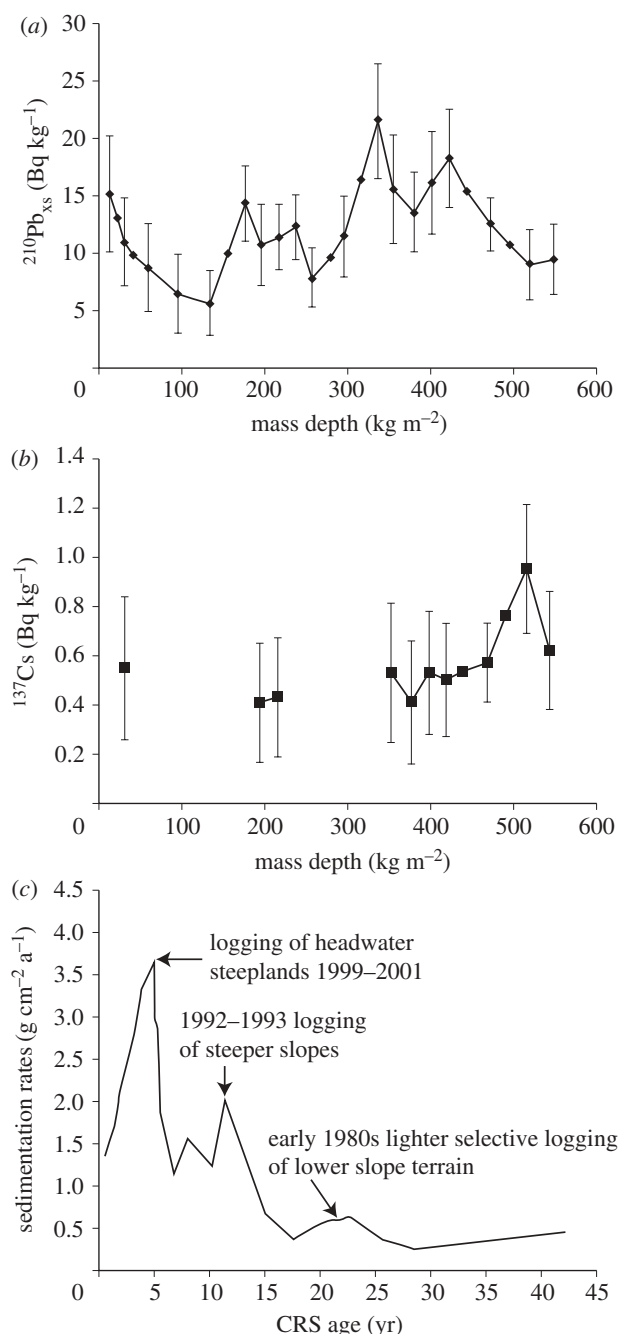


Figure 5. (a) Fallout ^{210}Pb , (b) ^{137}Cs and (c) inferred sedimentation rates (derived by recalibrating (and inverting) the Fallout ^{210}Pb record) in relation to upstream logging history of a 60 cm sediment core on a lateral bench of the River Segama at Danum Valley Field Centre. Age in panel (c) is the time (yr) before the date of sampling in 2007.

Segama. The early logging phase in the 1980s was largely confined to low-angle terrain and was very selective, with only lighter timbers being extracted, as logging roads did not reach the area and logs were floated down the river (W. Sinun 2010, personal communication). The intermediate peak tallies in timing with logging of steeper terrain in the 1992–1993 coupes to the south of Danum (A within figure 1a), where most of the area was logged using commercial logging practices and only a small section under RIL protocols. The most recent, largest peak in sedimentation rate coincides in timing with logging of very

steep terrain in part of the Segama headwaters (B in figure 1a).

The differences in the magnitudes of the peaks in sedimentation rate may be in part a product of differences in the degree of landsliding associated with the above logging phases. The density of landslides detected from the 1 : 20 000 aerial photographs for 1995 varied greatly within the mapped 225 km² area of the Upper Segama catchment around Danum Valley Field Centre (table 7). The differences in landslide density and frequency between areas of similarly steep terrain, but logged in 1992–1993 using RIL protocols and with commercial logging (using high-lead logging) are striking. Although 147 landslides (9.55 m² km⁻²) were recorded in the commercially logged 1992 Coupe and 72 landslides (2.55 m² km⁻²) in the 1993 Coupe, just five landslides (0.18 m² km⁻²) were detected in the 1992 RIL area (table 7), mainly because under RIL no logging is permitted on slope segments exceeding 25°. The variation in landslide density with terrain steepness is also clear, with a low density of 0.09 m² km⁻² found in the low-slope 1983 commercially logged coupe. The peaks in sedimentation rate in 1992–1993 and 1999–2001 recorded at the Segama core at Danum are probably in part the product of enhanced landsliding.

6. EROSIONAL IMPACTS OF CURRENT AND FUTURE CLIMATIC CHANGE

(a) Predicted and recent actual climatic change in Sabah

The main IPCC predictions (A1B scenario) for future climate of northern Borneo by 2080–2099 compared with 1980–1999 are for a 5–10% increase in annual rainfall, an increase in the frequency and size of extreme rainstorm events and a 3.3°C increase in annual temperature (lower than the global average reflecting the offsetting effect of increased rainfall and cloudiness) [28]. There is greater uncertainty about the future severity and frequency of El Niño–Southern Oscillation events, which tend to lead to dry periods in eastern Borneo.

The recent climatic record for long-term meteorological stations in northern Borneo and at the Danum Valley Field Centre appears to reflect some of these predictions. At Danum Valley Field Centre, the 5 year running mean of annual temperature has risen by 0.5°C from 26.7°C in 1986–1990 to 27.2°C in 2006–2010, with the highest annual mean of 27.6°C recorded in 2010 (figure 6). At Kota Kinabalu, the 5 year mean has risen by 0.8°C from 26.4°C in 1968–1972 to 27.3°C–27.5°C since 1990, though some of the increase might be due to expansion of the airport and urbanization. Long-term daily records at Sandakan and Tawau extending back to 1906 indicate a recent upswing in large rainstorms compared with 1947–1979, though frequencies had been almost as high in 1906–1940 (table 8). The upswing has intensified since 1999. Trends in the size of daily rainfalls of different return period vary, however, including between locations; thus at Sandakan, daily rainfalls of 1–2 year return period have increased, but more extreme rainfalls of 5 and 10 year return period have

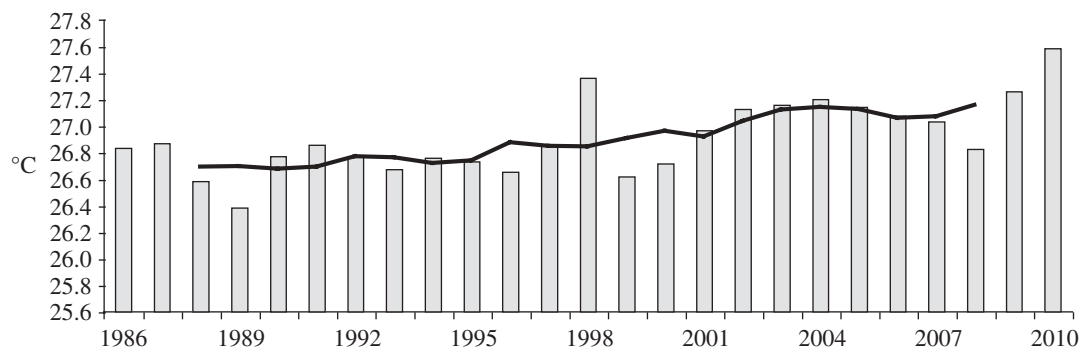


Figure 6. Annual temperatures at Danum Valley Field Centre 1986–2010. Solid line is the five-year running mean.

Table 7. Landslide frequency and density in the Danum area in relation to land-use, logging practice and terrain steepness. DVCA, Danum Valley Conservation Area.

land unit	terrain	number of detected landslides	total landslide area (m ²)	landslide density (m ² km ⁻²)
primary forest (DVCA)	moderate/steep	19	80 638	2.39
primary forest (Palum)	moderate	27	19 377	1.35
1992 RIL	steep	5	787	0.18
1992 coupe (commercial)	steep	147	262 561	9.55
1993 coupe (commercial)	steep	72	37 356	2.55
1988 coupe (commercial)	moderate	22	10 463	0.52
1983 coupe (commercial)	low slope	14	900	0.09

actually fallen since 1980, whereas at Tawau daily rainfalls from 1 to 10 year return period have all risen [29]. At Danum, annual rainfall in the years 1999–2010 was 14 per cent higher than in the years 1985–1998 and the frequencies of large daily rainfalls in excess of 50, 80 and 100 mm thresholds have shown substantial increases (table 9). There has also been an increase in dry period magnitude-frequency in Sabah since 1967, though the period 1877–1915 was equally drought-prone [30].

(b) *Likely erosional impacts of climatic change*

Uncertainties about the scale and nature of predicted climatic change—and about future land-use and land-management changes—preclude precise statements about hydrological and erosional impacts. Likely effects in the tropical rainforest zone as a whole have been considered in some detail elsewhere [29]. Of key significance would be the predicted increase in the magnitude-frequency of large rainstorms, which, if substantial, should result in (i) a major landsliding phase in areas of moderate and steep terrain, (ii) enhanced slopewash and pipe erosion, (iii) increased river bedloads and suspended sediment loads, (iv) increased flood frequency, and (v) increases in size, width–depth ratios and degree of shifting of river channels; effects would be greatly enhanced in agricultural and urban areas and in logged terrain where RIL protocols had not been followed.

Long-term monitoring at Danum supports some of these predicted impacts. Mean slopewash rates at 13 erosion bridge transects installed at primary forest sites in 1990 were over three times as high in the

wetter 1998–2010 period (0.87 mm a^{-1}) than they had been in 1990–1998 (0.24 mm a^{-1} ; table 9). As slopewash erosion at the sites is concentrated into years with very large daily rainfalls [5], the increase since 1998 may be linked to the increase in frequency of daily falls greater than 80 mm. Likewise, the sediment load of both primary and logged forest streams is disproportionately carried in the largest storm events [5,23]. Also differences in frequency of large rainstorms largely explain the major differences in sediment transport in the Baru stream between years 2003–2009 on the one hand and 2004–2005 on the other hand, as shown in table 3. Using models parametrized with current data (as in table 4) to predict sediment loads of a wetter and/or more storm-prone future may be inappropriate (except as a first estimate), however, as transport is also a function of sediment availability and supply to the stream network; the onset of a landsliding phase could well lead to a big increase in sediment supply and hence a much larger increase in load than models based on current data would suggest. Also increased fire frequency, resulting from either increased drought frequency or higher fuel loads and fire risks of a logged, fragmented forest, would lead to additional erosional episodes, as demonstrated in similar rainforest elsewhere in Sabah [31].

7. CONCLUSIONS AND POLICY MESSAGES

- Although the long-term monitoring and modelling results demonstrate that suspended sediment responses and erosion rates are significantly

Table 8. Changes in the frequency of large daily rainfalls of different threshold values at Sandakan and Tawau 1906–2010.

	annual frequency of daily rainfalls		
period	50 mm	100 mm	mean annual rainfall (mm)
Sandakan			
1906–1940	16.2	3.3	3186
1952–1979	14.8	2.4	3040
1980–2010	16.0	3.2	3057
1999–2010	17.3	4.3	3303
Tawau			
1906–1940	5.8	0.6	1887
1951–1979	4.6	0.3	1744
1980–2010	6.1	0.4	1919
1999–2010	6.6	0.7	2003

Table 9. The recent rise in annual rainfall and the frequency of large daily rainfalls and a parallel rise in mean slopewash rates at long-term erosion bridge transects sites in primary forest at Danum. Rainfall periods are calendar years. Slopewash periods are June 1990–July 1999 and July 1999–April 2010; the number of erosion bridge sites = 13; the number of measuring points = 37 per transect = 481; mean slope = 15.8° (range: 6°–31°).

period	annual rainfall (mm)	mean annual frequency of daily rainfalls (mm)			mean slopewash erosion rate (mm per year)
		>50	>80	>100	
1985–1998	2664	7.78	1.85	0.81	0.24
1999–2010	3049	10.42	2.58	0.91	0.87
change (%)	+14	+33	+40	+13	+248

reduced from 1995 to 1996 levels, the Baru catchment is not fully recovered 21 years after selective logging ceased in mid-1989. Although runoff from roads and skid trails can remain enhanced after 40 years [32], previous research at Danum [5] and elsewhere in southeast Asia [33–35] has demonstrated the dual, but short-term (less than 4 years) to medium-term (5–12 years post-logging) roles of logging roads in generating sources of sediment via road runoff or through causing landslides. Also enhanced slopewash rates on landslide scars in primary forest terrain in Puerto Rico lasted only 2 years after a landslide before revegetation reduced rates to pre-landslide levels [36]. This research, however, shows that (i) landslide scars and toe deposits can remain as important sources of sediment 14–16 years after landslides have occurred, and (ii) fresh landslips can be instigated along a mid-slope-oriented logging road 19 years after logging ceased—and hence that geomorphological effects can continue long after revegetation has occurred.

- (ii) There may be considerable potential for applying fallout radionuclide dating, which has been used

with success in Pacific islands closer to nuclear testing sites [37,38], and sediment fingerprinting techniques more widely in humid tropical environments. Despite the low fallout ^{137}Cs activity concentrations, the 1963 peak was still apparent in the Segama bench core and allowed time calibration of the ^{210}Pb record and the reconstruction of a curve of sedimentation rates for the upper Segama spanning the logging period. Likewise, the multi-proxy sediment fingerprinting approach appears to have been effective at the small-catchment scale in indicating from which tributary sub-catchments current sediment is being derived. Combining these approaches may prove more difficult at a large catchment scale because of (i) sediment storages and delays between upstream tributaries and downstream floodplain locations and (ii) possible changes in elemental signatures of the bed-sediment of individual tributary catchments through time, particularly with enhanced landslide activity (and subsoil and weathered rock inputs) during logging phases [39].

- (iii) Enhanced landsliding, which has major ramifications for the fluvial system downstream, is considered the main danger of predicted climatic change in the region, not only because of its link to any increase in the magnitude-frequency of large rainstorms, but because landslide frequency is sensitive to forest disturbance and land-use change. The analysis of long-term daily rainfall series for Sabah suggests that some categories of large rainstorm may be already increasing in frequency.
- (iv) Impacts of both climatic change and human activities in the region can be reduced greatly if land-use and land-management strategies are followed. The landslide density data presented in this paper show that strict adherence to RIL (in which slopes above 25° are left unlogged) largely avoids causing landslides. Keeping all slopes above 25° under forest would be a wise land-use strategy as are current moves by some plantation companies to abandon cultivation of such slopes and allow forest regeneration.

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