20 Spatially significant effects of selective tropical forestry on water, nutrient and sediment flows: a modelling-supported review

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INTRODUCTION

Selective forestry is a set of commercial forestry practices that involves the selective removal of particular trees within an 'annual logging coupe' of forest (Conway, 1982). Selective harvesting within 'natural forests' (i.e. those forests that have not be clear-felled for non-forest uses or converted to plantation or agro-forestry) covers a very wide range of practices, including high-lead and tractor yarding, harvesting of only large, commercial trees, protection of riparian vegetation along rivers, and protection of forest on very steep hills. As a consequence, the intensities of the impacts on the water environment (i.e. water, nutrient and sediment systems) are expected to be very varied. Some of these impacts can be profound. One of the most significant environmental impacts of all types of forestry operations within the humid tropics is accelerated soil erosion (Bruijnzeel, 1992). The resultant input of sediments into rivers leads to damage to fish populations (Martin-Smith, 1998), reduced quality of water supplies, reductions in channel capacity which affects flood risk and boat traffic (Sheffield *et al.*, 1995), and the inundation of offshore corals (MacDonald *et al.*, 2001).

Development of selective harvesting techniques when applied to natural forests in the tropics are currently being focused on so-called 'Reduced-Impact-Logging' (RIL) or 'closely supervised' methods which aim to improve the 'sustainability' of timber production and reduce wider environmental damage. These RIL procedures include optimising skid trail networks, given a knowledge of the exact location of each tree to be felled, minimising stream crossings, minimising 'skid-trail' earthworks, maintaining canopy-cover over skid trails, construction of water-bars on unused haulage roads, and critically, careful supervision of all forestry operations (Abdul Rahim *et al.*, 1997; Pinard *et al.*, 1995; van der Hout, 1999). Additionally, where natural forests have been logged and regeneration has been poor, then 'enrichment planting' of commercial (and non-commercial) trees is beginning to be used as part of selective forestry management (Adjers *et al.*, 1995; Kobayashi *et al.*, 2001).

Research into the water-related impacts of natural forest management is important throughout tropical regions given (i) the economic importance of such forestry, (ii) the desire to identify the least damaging forestry practices, and (iii) the large areal extent of natural forest. For example, within South and South East Asia, natural forests (managed and undisturbed) currently cover 25% of the land area while within the continents of South America and Africa they occupy 47 and 12%, respectively (Iremonger *et al.*, 1997).

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Scale and variability

Selective forestry is managed by dividing the forestry concession into annual harvesting coupes, typically 10–50 km^2 in area. At this scale, processes controlling the pathways of water, nutrients and sediments are highly heterogeneous. Tropical water pathways are spatially variable, in part, because subsurface flow often emerges only in near-stream areas, some slope sections have areas of extensive and highly conductive soil piping (Chappell *et al.*, 1998; Jones, 1990), and permeability variations are observed along the soil catena (Chappell and Ternan, 1992). Tropical nutrient pathways will be variable because of the heterogeneity of (i) the controlling water-paths and catenal changes in soil chemistry (Whitmore and Burnham, 1969; Dixon, 1986), (ii) weathering rates of different parent rocks, and (iii) the rate of nutrient release/uptake with different vegetation associations. Tropical erosion and sediment delivery will also vary as a result of patterns in the water-paths but also because of changes in the soil stability resulting from changes in the underlying rock (Rahman, 1993), local topography (Larsen and Torres-Sanchez, 1998) or root-anchoring properties of different plant species (Collison and Anderson, 1996). Superimposed on this pattern of natural processes, selective logging will generate new local patterns of land-use including zones of surfaced haulage roads (with slope cuts), skid trails, highlead foci, lightly-impacted forest and protection forest. New patterns of water-related processes, arising from an interaction of their natural distribution and the new land-use patterns will then result. Clearly, this inherent heterogeneity means that statistically meaningful changes to the rates and distribution of water processes need to be assessed over scales that capture a distribution of the natural and anthropogenically-induced landforms. The scale of the 'experimental catchment' of perhaps 0.1–50 km^2 has been seen by hydrologists and geomorphologists as this fundamental scale of integration (Gregory and Walling, 1973). While the impacts of any intensity of land-use change can be observed at the local or individual landform scale, clearly, it is those land-use practices that *can be demonstrated* to have very significant impacts over 'experimental catchment' scales, which we could call the 'landscape scale', where improvements to the practices would give real economic and environmental benefits. Further, we need to demonstrate that there is indeed a measurable impact at these landscape scales before we need to consider the complex physical and chemical processes that might have led to the change.

Catchment-scale studies

Very few catchment studies have examined the effect of selective forestry on water-related processes (Bruijnzeel, 1989a; 1990; 1992; 1996; Abdul Rahim and Harding, 1992), making it very difficult to separate the individual effects of climatic regime, geological setting and forest type from those of specific selective forestry practices. Even with the results of each catchment experiment being taken only as a 'case study with a set of known environmental variables', the quality of the individual data-sets remains paramount with such limited numbers of studies. Ironically, the need to utilise only high quality data-sets (Bruijnzeel, 1991; 1996) limits further the choice of published results for detailed examination.

The 'quality' of the catchment data-sets and interpretations will be dependent on a number of factors:

(1) The first factor is accuracy of the water, nutrient or sediment variables measured at specific sampling locations. For example, Bruijnzeel (1989a; 1991) has questioned the evapotranspiration and nutrient budgets of many tropical catchment studies because the authors have assumed implicitly that no subsurface water or nutrients cross (surface-defined) catchment divides. Similarly, Douglas *et al.* (1992) note that where tropical sediment budgets have not been derived from data collected by automatic storm-sampling equipment, highflow concentrations will be characterised inadequately and budgets under-estimated.

(2) The second factor is the inability to separate land-use effects from those caused by natural trends and cycles in the local climate. This effect is dependent, in part, on the number of years of record that can be examined before and after the land-use change. The study of Subba Rao *et al.* (1985) on the effect of plantation thinning in Rajpur Forest (North India) is good in this respect, as it utilises nine years of rainfall-runoff data from the pre-thinning period. Despite the length of their records, however, the impact of the plantation thinning on fortnightly water-yield was not observable.

While differences between a manipulated catchment and a nearby 'control' (un-manipulated) catchment can be identified through natural climatic fluctuations, the relative magnitude of the anthropogenic impacts may, however, depend on whether they took place during a wet or a dry period (Abdul Rahim and Harding, 1992; Douglas *et al.*, 1999). Thus use of 'paired catchments' does not remove all of the effects of climate dynamics.

(3) The third factor is a difference in size of the manipulated and control catchment. Experimental catchments with similar rainfall, soil/rock type and vegetation, but small differences in size, perhaps less than a factor ten, may have a different balance of surface and subsurface flow processes (Chappell *et al.*, 1999a). This will affect the sensitivity of the catchment to land-use change, with a catchment having greater proportions of surface flow being more sensitive to terrain modifications.

(4) The fourth factor is the danger of interpolating the effects for selectively-managed forest from the behavioural range derived from (a) catchments in an undisturbed state, and (b) after clearfelling. This is because the selective removal of trees under a selective management system may not give the same effect as partial clearfelling (i.e. removal of large patches of forest) even where the same regional timber yields are obtained. There are several reasons for this. First, the selective removal of large, commercial trees leaves younger trees, saplings and seedlings that rapidly take advantage of the new micro-climate generated. This means that in many areas, the ground surface is soon protected from impacting rain-drops, which may increase infiltration and reduce erosion (Douglas *et al.*, 1995). Further, some colonising vegetation may have greater transpiration and wet-canopy evaporation rates in comparison to areas completely cleared of vegetation (Swank *et al.*, 1988; Bidin, 2001; Chappell *et al.*, 2001; Restom and Nepstad, 2001). A second important issue why selective forestry should not be considered as 'partial clearfelling' relates to the haulage road network. With selective forestry operations in natural forest the road network is constructed with the 'consideration' (though not complete assurance) of access during the next phase of selective logging perhaps 30–60 years ahead. As a result, it is often considered better to built roads close to ridge tops rather than in the wetter valley floors. In contrast, clearfelling may only require access during the single clearance process and hence not necessitate the construction of roads with any longevity.

(5) The fifth factor is the length of observations of the impact. Most studies on the impact of selective forestry are carried out over only the one to three years of the haulage road construction, harvesting operations and immediate post-logging phase. These studies clearly allow only limited assessment of the persistence of the impacts, an issue critical in assessing the 'environmental sustainability' of forestry operations. Issues that are important in this respect include: (i) the re-vegetation of skid trails and consequent reduction in overland flow and erosion (Douglas *et al.*, 1995), (ii) accelerated growth of vines and pioneer trees with different wet-canopy evaporation (Chappell *et al.*, 2001) or transpiration rates (Becker, 1996; Eschenbach *et al.*, 1998; Davies, 1998), and (iii) persistent instability of road cuts (Chappell *et al.*, 1999a).

(6) The sixth factor is the quality of the records detailing the type of forestry practices adopted, timber yields extracted, and the spatial distribution of the extraction systems (i.e. skid trails, log landings and highlead foci). Newly established catchment studies have benefited from recent moves towards 'Reduced Impact Logging' (RIL) and 'certified' harvesting systems that has meant that forest management agencies and companies have improved the quality of their forest management records.

Given these issues, we seek here to assimilate the results of studies of selective forestry impacts on catchment-scale water, nutrient and sediment flows in tropical natural forests, and also to examine the value of data-based modelling in the assimilation of the most reliable case studies.

WATER FLOWS

Selective forestry may affect the pathways of precipitation (e.g. rainwater and fog-drip) from the tropical rainforest canopy and terrain to the river or back to the atmosphere as evapotranspiration.

Evapotranspiration, catchment water-balance and water yield

An integral component of the selective logging of natural forests is the construction and use of lorry haulage roads (sometimes stone-surfaced), 'skid trails' (i.e. the tracks used by logging tractors), and 'log-landing areas' where timber is loaded on to the lorries. If these surfaces are impacted by frequent use, vegetation re-growth may be inhibited locally. Rates of total evaporation (evapotranspiration) from these bare earth surfaces are likely to be less than those from the vegetated surfaces that they replace. Additionally, 'highlead yarding', where timber is dragged from all directions to a central mast (Conway, 1982), leaves patches (perhaps 20–50 m in diameter) of shrubs (e.g. Zingiberaceae), herbs and sprawlers distributed about the natural forest (Bidin, 2001; Chappell *et al.*, 2001). This ground vegetation may have transpiration rates less than high forest with its greater rooting depth and leaf area index (Roberts *et al.*, 1993). Recent measurement and modelling work in Guyanan rainforest, South America (van Dam, 2001), has indeed suggested that the selective removal of climax trees leads to a reduced total evaporation in the immediate area.

The effect of clearfelling experimental catchments covered by most types of tropical natural forests is well attested – complete clearance results in greater riverflow or 'water yield' (Oyebande, 1988; Bruijnzeel, 1990; 1996; 2001). The possible exception to this is montane forest with its high precipitation input as fog-drip, though the data are too limited for generalisation (Bruijnzeel, 1996; 2001; Hafkenscheid, 2000). As selective logging generates smaller gaps in the forest, where new growth of pioneer trees, accelerated growth of younger and smaller commercial trees and/or (vine growth takes place, the marked increases in water yield seen with clearfelling climax trees may be partly offset by the rapid growth of water-demanding pioneer trees and vines. Restom and Nepstad (2001) and Eschenbach *et al.* (1998)

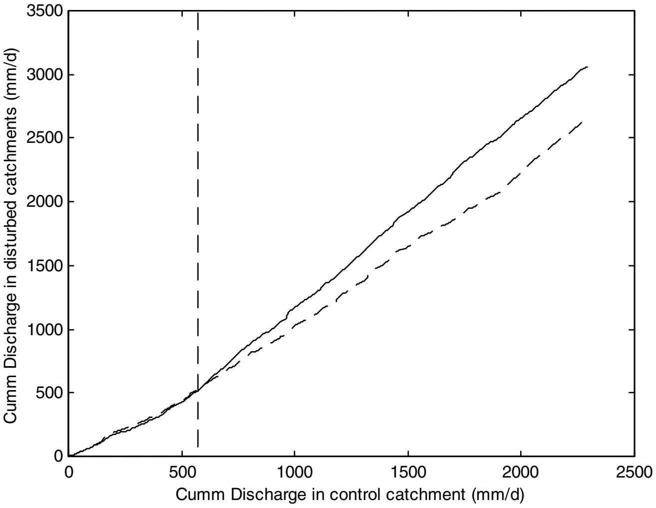

Figure 20.1 The double-mass curve of riverflows for the conventionally-logged catchment versus the control catchment (black line), and RIL catchment versus the control catchment (broken line), Bukit Berembun, Negri Sembilan, Malaysia. The vertical dashed line indicates the start of forestry activities (July 1983) within the catchments.

have noted high rates of transpiration from vines in secondary Amazonian forest and pioneer trees in East Malaysian rainforest, respectively.

The most reliable catchment water-balance study that captures the effects of selective logging of tropical natural forests is that undertaken within the Bukit Berembun catchments in Peninsular Malaysia. Three catchments (2°46′ N, 102°6′ E) were installed within 'lowland dipterocarp rainforest' on Acrisol soils derived from a weathered granite geology (Abdul Rahim, 1990; Abdul Rahim and Zulkifli, 1994). One catchment was kept as a natural control ('C2'), one was selectively-harvested by 'unsupervised' methods ('C1') and one selectively-harvested by 'supervised' or 'Reduced-Impact-Logging' (RIL) procedures ('C3'). The 'San-Tai-Wong' logging method (which involves the use of both tracked-skidders and winch lorries) was used within both harvested catchments. The data-series derived from these catchments were chosen for analysis, given that high quality riverflow data, collected at 120° V-notch weirs, is available for a pre-logging phase and a relatively long record for the logging and 'terrain recovery' phase.

The double-mass curve (Searcy and Hardison, 1960) of the two selectively-logged, Bukit Berembun river catchments *versus* the control catchment shows an increased water-yield from the beginning of the road construction and harvesting in July 1983 through to the end of intensive monitoring in 1989 (Figure 20.1). The catchment with the greater harvesting intensity (i.e. 40% timber extraction rather than 33%; Abdul Rahim and Harding, 1992) resulted in a greater increase in water-yield. This selective-logging produced a gradual increase in water-yield over the initial harvesting period, compared with the step change in the double-mass-plot observed for the clearfelled Sungai Tekam 'Catchment A', also in Peninsular Malaysia (see Figure 20.5 in Abdul Rahim, 1988). Interestingly, the greater water-yields following selective forestry persisted over the six years of intensive monitoring after the harvesting phase (Figure 20.1). Bidin (2001) examining catchment water yield of a selectively managed forest in East Malaysia from one to eight year's post-disturbance, could not detect a change in the water balance with forest recovery (above the changes associated with climate dynamics). Over the whole post-logging period, average water-yield (1984–1989) of the commercially-logged, Bukit Berembun catchment increased 1.47-fold (+129 mm) and the RIL-catchment 1.24-fold (+66 mm) compared with the undisturbed, control catchment.

In some contrast to the Bukit Berembun study, Jetten (1994) noted no significant change in catchment water balance following light selective harvesting of Guyanan rainforest of South America. While not being directly applicable to the impacts of selective forestry on water balance in tropical natural forests, the light logging (20 m^3/ha) catchment study of Gilmour (1977) in Queensland, Australia, and the 20% thinning of a *Shorea* plantation covering a catchment in northeast India (Subba Rao, *et al.*, 1985) similarly failed to note observable changes in the water balance following timber harvesting. Failure to observe water balance changes directly after timber extraction may have been explained by accelerated growth of existing trees within the new light environment, offsetting the effect of the removal of climax trees.

The relatively small increase in water yield within Bukit Berembun might be explained by a catchment-average reduction in the transpiration and/or wet canopy evaporation. The work of van Dam (2001) in Guyana shows that in the gaps created by selective harvesting, transpiration may be reduced in comparison with that of the original climax trees. Thus reduced transpiration from the greater number of canopy gaps could explain the increase in water yield following selective felling. Other plot-based work within selectively-managed forest in Indonesian Borneo, suggests that catchment water-yields might be increased by reduced rates of wet-canopy evaporation (or 'interception-loss') when climax trees are removed (Asdak *et al.*, 1998). A more recent study conducted in similar selectively-managed forest in neighbouring Malaysian Borneo has, however, shown that rates of wet-canopy evaporation can be greater in highly damaged patches of rainforest compared with that in remnants of climax forest (Bidin, 2001; Chappell *et al.*, 2001). Clearly, new studies undertaken through the first cycle of selective logging of natural forests are needed to apportion catchment-scale evapo-transpiration more definitively into the components of transpiration and wet-canopy evaporation.

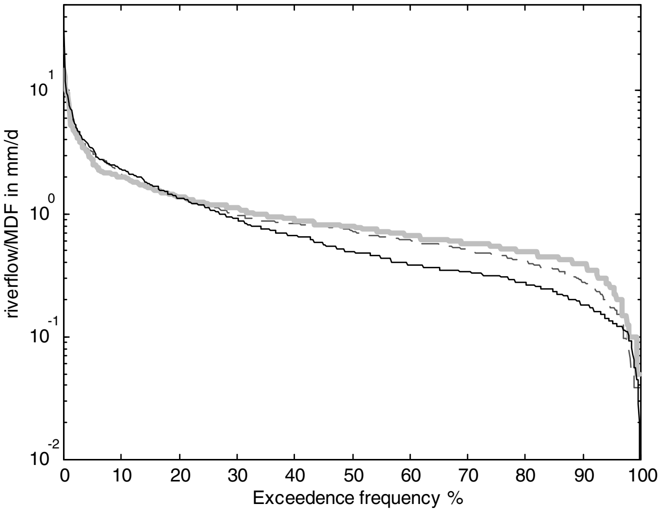

Figure 20.2 The flow-duration curves using data for the 1981–2 period for the control catchment (grey line), the conventionally-logged catchment (broken black line), and the RIL catchment (solid black line). Bukit Berembun riverflow is normalised by the mean daily flow (MDF).

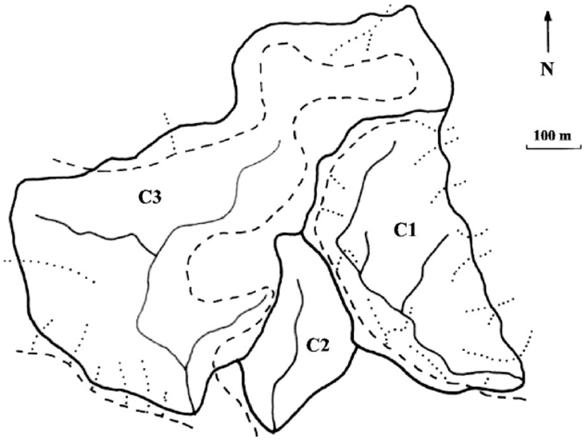

Figure 20.3 A map of the Bukit Berembun C1, C2 and C3 catchments in Peninsular Malaysia, showing catchment divides (wide, solid lines), streams (narrow, solid lines), timber haulage roads (broken lines) and skidder trails (dotted lines).

Flow-paths and rainfall-runoff behaviour

The dynamic characteristics of a river are integrated measures of the varied responses of complex water-pathways draining to that river. If there are substantial changes in catchment water-paths resulting from forestry operations, then they will be reflected in (i) the riverflow dynamics and (ii) the mathematical relationship between the incoming rainfall and outgoing riverflow.

The construction and use of forestry haulage roads and skid trails has been demonstrated to have a *local impact* on rates of infiltration into Humic Acrisols soils in Costa Rica (Spaans *et al.*, 1990), Haplic Acrisols (Malmer and Grip, 1990) and Alisols (Van der Plas and Bruijnzeel, 1993) in East Malaysia, and Ferralsols in Guyana (Jetten *et al.*, 1993). This has then had a local impact on the amounts of water travelling over the ground surface as ‘infiltration-excess overland flow’ (Baharuddin, 1995). The key issue is whether these impacts, which may be significant at certain points within a catchment or forest-logging-coupe, are extensive enough to impact at the landscape-scale itself and thereby affect the river behaviour.

The range of flows within a river can be characterised graphically by estimation of the flow-duration curve or FDC (Searcy, 1959). A river’s flashiness can then be estimated from the slope of a specified segment of the FDC. If we examine the data for the Bukit Berembun catchments again – prior to any forestry activities (1981–2) – the three Bukit Berembun catchments have different natural flow regimes (Figure 20.2). The C3 catchment was much more flashy prior to RIL logging compared with the other two catchments. The smallest of the catchments, the 4.6 ha C2, had the greatest lowflows per unit catchment area (in relative and absolute terms) and the largest, 30.8 ha C3, had the least lowflow. This is not expected, as water that has percolated to a significant depth has more likelihood of returning to the ground surface before, or ‘upstream’ of, a river gauging structure as catchment size increases up to 1 km^2 (Chappell *et al.*, 1999a). As the smallest catchment (C2) is on only the lower slopes of the hill that all three catchments occupy (Figure 20.3), it may be that deep (and slow) preferential flow (within the weathered granite) from the other catchments is feeding C2 rather than their own lower catchments.

Following selective harvesting, both conventional and RIL logging techniques produced an increase in the highflows as expressed in the Q10 statistic – the riverflow equalled or exceeded for 10% of the time (Table 20.1). In the case of the conventional logging (C1 catchment), Q10 flows were increased by 1.43-fold directly after harvesting, at a time when the control catchment highflows reduced slightly. These effects are larger than those observed by the studies of Subba Rao *et al.* (1985) and Gilmour (1977), though the studies are not directly comparable. Subba Rao *et al.* (1985) monitored a 9% increase in peakflow in the first year of a 20% thinning of a *Shorea* plantation catchment in north India, while Gilmour (1977) failed to observe any change in peakflows during the light logging catchment study in Queensland, Australia.

The ratio of the riverflow observed for at least 30% of the time to that observed for more than 70% of the time – the Q30/Q70 statistic, has been used as a measure to characterise the ‘flashiness’ of river regimes within temperate catchments (Ward, 1981). The greater the value of the statistic, the greater the flashiness of the river behaviour. Table 20.2 shows these statistics calculated from the FDCs for the Bukit Berembun riverflows (normalised by mean daily flow) (Figure 20.4). The undisturbed, control catchment (C2) maintained a very similar Q30/Q70 statistic throughout

Table 20.1. *Daily riverflow (mm/d) equalled or exceed for 10% of the time* ($Q_1$0 *statistic describing highflows) within the Bukit Berembun experimental catchments*

	C1 Unsupervised logging (13.3 ha)	C2 Control (4.6 ha)	C3 Reduced-impart login (RIL) (30.8 ha)
Pre logging (1981–2)	1.4562	1.5224	1.6001
Logging and recovery (1984–5)	2.0802	1.4285	1.7489
relative change from 1981–2 period	Increase 1.430-fold	Reduce 0.938-fold	Increase 1.090-fold
Logging and recovery (1984–5)	1.5224	1.6001	1.9706
relative change from 1981–2 period	Increase 1.045-fold	Increase 1.051-fold	Increase 1.232-fold

Table 20.2. Q_{30}/Q_{70} *River flashiness statistics for the Bukit Berembun experimental catchments; riverflows in the FDC are normalised by the respective mean daily flows (MDF)*

	C1 Unsupervised logging (13.3 ha)	C2 Control (4.6 ha)	C3 Reduced-impart login (RIL) (30.8 ha)
Pre logging (1981–2)	1.9815[a]	1.9568[a]	2.6905[a]
difference to 'control'	0.0247	–	0.7337
direction of difference	Same	–	Much more flashy
Logging and recovery (1984–5)	2.2039	1.9545	2.4851
absolute change[b]	0.2214	0.0023	0.2054
direction of change	Slightly more flashy	Same	Slightly less flashy
Logging and recovery (1984–8)	1.9390	1.9524	2.1783
absolute change[b]	0.0425	0.0044	0.5122
direction of change	Same	Same	Much less flashy

[a] A greater value indicates an increase in 'riverflow flashiness' (i.e., a steeper curve).

[b] Absolute value of the Q_{30}/Q_{70} statistic for 1981–2 minus that for either 1984–5 or 1984–8.

the whole study period. The conventionally logged C1 catchment became slightly more flashy immediately after harvesting activities but then recovered to the pre-logging condition within a few years (Figure 20.4b). In some contrast, the river regime within the RIL logged catchment (C3) became and remained more damped (Figure 20.4c) in comparison with the pre-disturbance condition.

The contrasting behaviour of the two selective-logging systems is interesting. The increase in lowflows relative to highflows following selective-logging of the C3 catchment may be attributable to reduced transpiration which takes place throughout inter-storm periods. While absolute values of lowflow have increased with logging in the C1 catchment, the overall response may have become more flashy because of greater increases in the higher flows. This may have been because of the greater lengths of indurated or compacted road surfaces with the conventionally logged C1 catchment compared with the supervised RIL harvesting in C3. The length of haulage roads and skid trails in the conventionally logged C1 is 0.14 km ha^{-1} but 0.10 km ha^{-1} within RIL (Abdul Rahim and Harding, 1992). This may have led to greater quantities of rapid flowing surface flows on road surfaces or in roadside drains that would give slightly more peaked river hydrographs (see e.g. Macdonald *et al.*, 2001 work in the US Virgin Islands). With vegetation re-growth on skid trails and unsurfaced haulage roads, surface flow would reduce, as demonstrated in the East Malaysian plot studies of Douglas *et al.* (1995), thus reducing storm peaks. The slightly more flashy behaviour of the conventionally logged C1 catchment could also be explained by a marked reduction in wet-canopy evaporation which then allowed much more water to enter the catchment system during storms (cf. Asdak *et al.*, 1998). With vegetation recovery, rates of wet-canopy evaporation would then increase again, damping storm behaviour within rivers. While this second explanation is consistent with the results of C1, it would not be totally consistent with those of C3, so we suggest that the mechanism of small changes to the quantities of surface flow is the more likely explanation.

Interpretation of flow-duration curves is somewhat dependent on the particular sections of the FDC that are used to derive the statistics. Dynamic modelling could be used to derive the

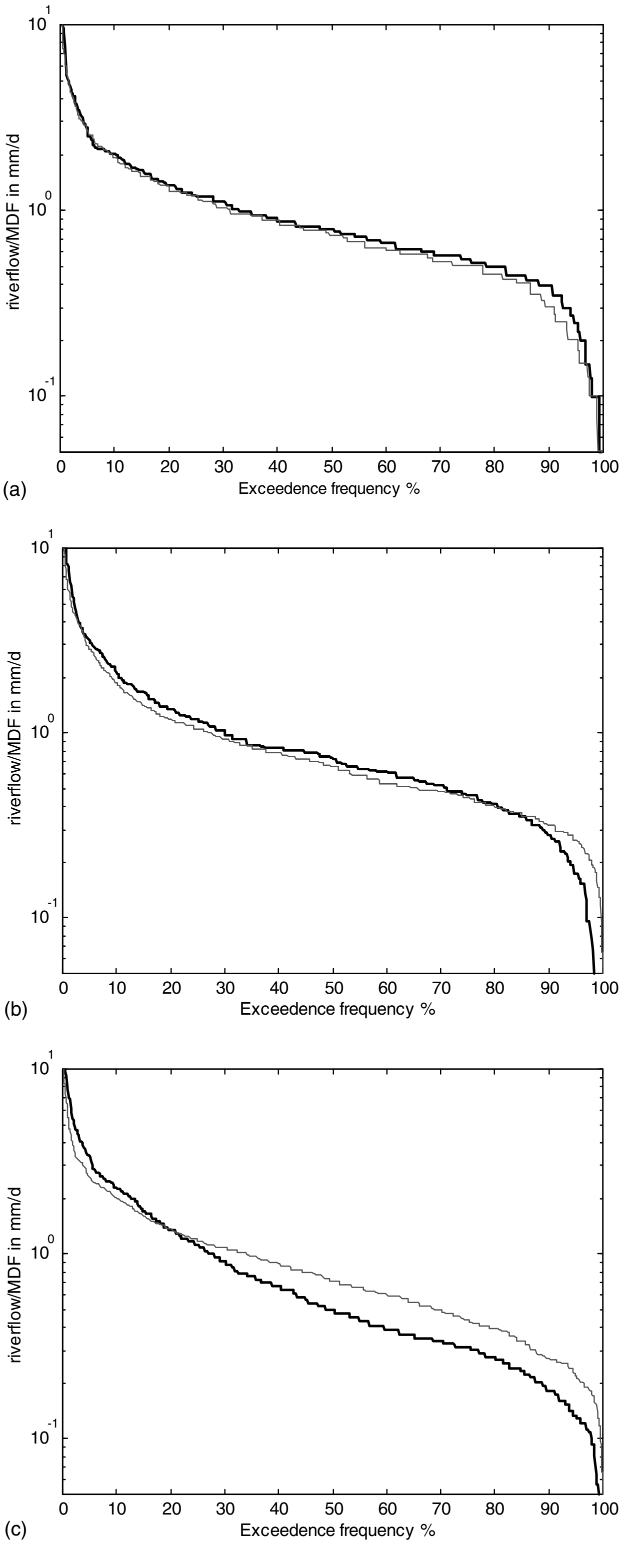

Figure 20.4 The flow-duration curves for the period 1981–2 (black line) and period 1984–5 (grey line) using riverflow data for: (a) the control catchment, (b) the conventionally-logged catchment, and (c) the RIL catchment. All Bukit Berembun data are normalised by the respective mean daily flows (MDFs).

whole range of response characteristics within a single model. Indeed, a model's parameters can be described as the model's 'Dynamic Response Characteristics' or DRCs (Jakeman *et al.*, 1993; Post and Jakeman, 1996). Any changes in these parameters following the establishment of forestry may be caused by the subsequent vegetation and/or terrain modifications. Young and Beven (1994) state that such parameter interpretation is, however, only successful with parsimonious modelling approaches (i.e. those with simple model structures, requiring only few parameters). This is because of the increasingly acknowledged problem of parameter interaction during the identification process. 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 and objective statistical inference (Young *et al.*, 1997). Under the Wheater *et al.* (1993) classification of catchment hydrological models, the DBM model, like the IHACRES model of Jakeman and Hornberger (1993), is a type of 'hybrid metric-conceptual model'. Middleton (2000) provides a good introduction to modelling with transfer functions. Elsewhere in this volume, Schreider and Jakeman and Barnes and Bonell elaborate on IHACRES and other DBMs and their links with DRCs.

The DBM modelling approach was applied (within MATLAB) to the same daily data-series for the conventionally-logged Bukit Berembun experimental catchment (C1) for a two-year period (1981–2) just prior to the start of forestry in July 1983, and a two-year period shortly after the activity had started (1984–5). The non-linearity in the catchment behaviour was characterised using the 'Store-Surrogate Sub-Model' (SSSM; Young and Beven, 1994; Chappell *et al.*, 1999a; Young, 2001). Many different model structures were then used to attempt to describe the linear component of the relation between incoming rainfall and the outgoing riverflow. The 'best model' structure was the one that had the highest efficiency (cf. Nash and Sutcliffe, 1970), while maintaining a large negative YIC value (Young Information Criterion: Young, 2001). Small negative or positive YIC values indicate that the information content of the observed data-series is insufficient to justify the level of complexity (i.e. number of model parameters) of that particular model structure.

A simple, first-order model structure was seen to best capture the rainfall – riverflow behaviour of the C1 catchment during the first two-year period, 1981–2 (Figure 20.5a.), and explained 89% of the variance in the riverflow dynamics. In transfer function form, the optimal model structure was:

$$q(k) = \frac{P_0 - P_1 z^{-1} - P_2 z^{-2}}{1 - \Re z^{-1}} r_{\text{eff}}(k) \qquad (20.1)$$

where $q(k)$ is the riverflow at the time index k, $\Re$ is the recession or lag parameter, P_0, P_1 and P_2 are the three system production or

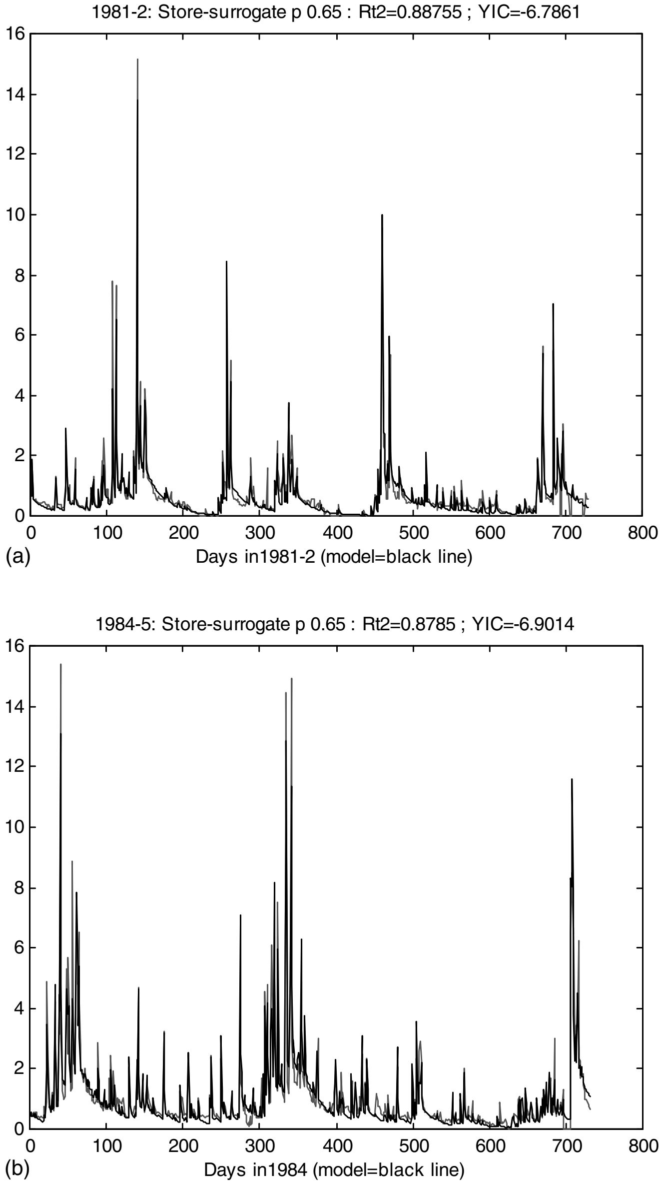

Figure 20.5 Observed (grey broken line) and simulated (black solid line) riverflow generated by the Bukit Berembun C1 catchment during: (a) 1981–2 and (b) 1984–5.

gain parameters, z^{-1} is the backward shift operator (i.e., $z^{-i}\, r(k) = r(k-i)$) which allows the expansion to higher-order models, and r_{eff} is the transformed rainfall input (Young, 1984). A pure time delay to the initial response (δ) was not necessary with the Bukit Berembun data-series. The model shown with the parameters of the linear component of the model applied to the C1 1981–82 data-series is:

$$q(k) = \frac{0.0393 - 0.0276z^{-1} - 0.0068z^{-2}}{1 - 0.9575z^{-1}} r_{\text{eff}}(k) \qquad (20.2)$$

The initial transformation on the rainfall input to describe the behavioural non-linearity (r_{eff}), was described by:

$$r_{\text{eff}}(k) = r(k)\{q(k)^{\beta}\}; \text{where } \beta = 0.65 \qquad (20.3)$$

where r_{eff} is the transformed input, $r(k)$ is the catchment-average rainfall at time index k, $q(k)$ is riverflow at time index k, and is the estimate of the power-law exponent (after Young and Beven, 1994). To maintain the same mass balance, the transformed input was then normalised in relation to the catchment-average rainfall to give the 'normalised transformed input' (see Chappell *et al.*, 1999a). This non-linear transform, described as the 'Store-Surrogate Sub-Model', captures the non-linear effects resulting from subsurface water storage (Young and Beven, 1994; Young *et al.*, 1997), wide macro-micropore flow distributions and/or layered soils.

Two key DRCs of this overall model structure capture the catchment's responsiveness – the power-law exponent of the non-linear transform (β) and the recession or lag parameter ($\Re$). As the power-law exponent was held constant (at 0.65) for both time periods (1981–2 and 1984–5), any change in the catchment responsiveness will be compounded within the recession parameter ($\Re$). The recession parameter is usually presented in terms of a time constant (TC), where:

$$\text{TC} = \frac{-t_{\text{base}}}{\log_e(-\Re)} \qquad (20.4)$$

and t_{base} is the time-base of the data-series (i.e. daily time-steps for the Bukit Berembun data-series). This TC term can be equated either with the residence time of the water within the whole catchment (Young, 1992) or within the saturated downslope soil-rock.

The resultant TC or residence time for the C1 catchment prior to conventional selective logging was 23.059 ± 0.189 days. This is a relatively long residence time and probably relates to the percolation of a significant proportion of water deep into the underlying weathered granite (Abdul Rahim, 1990; George, 1992) before emerging in the river. For comparison, the similarly-sized Baru catchment in East Malaysia that was within relatively impermeable mudstones (Chappell *et al.*, 1998), had a residence time of only 47 minutes with a similar model structure (Chappell *et al.*, 1999a).

During the logging and immediate post logging period, the model efficiency remained similarly high, with 88% of the riverflow variance being explained (Figure 20.5b). Critically, the residence time for the logging period remained virtually unchanged at 23.469 ± 0.167 days. Therefore, by characterising changes in the catchment's responsiveness with a single characteristic that describes the whole range of behaviour, no significant change in the river's flashiness is observed. This characteristic, and hence associated interpretations, are likely to be more robust than characteristics derived from only local parts of the flow-duration-curves described earlier. We might then ask, why do phenomena such as forestry road construction not always have a significant impact on catchment responsiveness? First, tropical rainforest slopes in Africa (e.g. Dabin, 1957), South America (e.g., Cailleux, 1959) and SE Asia (e.g. Chappell *et al.*, 1999a) usually generate only a few per cent overland flow per unit slope area. Perhaps the exceptions are those areas experiencing very intense tropical cyclones (e.g. Bonell *et al.*, 1983). Secondly, the surface area of haulage roads or (well-used) skid trails that would increase the proportion of overland flow, occupies a relatively small area of the typical size of experimental catchment. For example, they occupy only 2.1% and 4.9% of the Baru and Bukit Berembun C1 catchments, respectively. Thirdly, visual observations during extreme storms (N. A. Chappell, *pers. observ.*) indicate that even where overland flow is generated on road surfaces, a significant proportion will drain on to surrounding slopes where it will infiltrate rather than enter a stream channel directly.

Research needs

While the impact of selective forestry on water yield seems relatively small compared with the impact of clearfelling and conversion from natural forest (cf. Bruijnzeel, 1990; 1996; 2001), understanding the relative role of changes in the transpirational losses compared to changes in the wet-canopy evaporation losses remains uncertain. New studies undertaken through the first cycle of selective logging of natural forests are needed to apportion catchment-scale evapo-transpiration accurately into the components of transpiration and wet-canopy evaporation. Given the complexity of the canopy generated by selective harvesting, these studies may need to combine *direct measurements* of: (i) catchment-wide, transpiration (cf. Sellers *et al.*, 1995), (iii) catchment-wide, wet-canopy evaporation (cf. Bidin, 2001), and (iii) lumped losses from catchment scale, precipitation-minus-riverflow (P-Q) data (cf. Hudson *et al.*, 1997). As the Bukit Berembun catchment failed to show a return to pre-logging water-yields some six years post activity, *long records post logging are important* for this analysis (cf. Swank *et al.*, 1988).

The analysis of flow-duration-curves and a data-based numerical model did not give fully consistent results, though large, sustained impacts on river flashiness were not observed by either method. The small inconsistency in the interpretations may, at least in part, be related to uncertainty in whether there is a sufficient volume of surface flow localised on newly created road surfaces to short-circuit the catchment's subsurface system and affect the river hydrograph directly. New catchment experiments with road and trail networks fully instrumented to measure a significant proportion of all of the road-related surface flows are needed to provide more concrete evidence of road impacts on river responsiveness.

NUTRIENT FLOWS

Most hydro-chemical studies examining the impacts of temperate and tropical forestry indicate that timber harvesting results in accelerated nutrient flows along catchment rivers (e.g. Bruijnzeel, 1990; Stevens *et al.*, 1995; Swank, 1988). This has the potential to both (a) reduce the fertility of the catchment system being harvested (Attiwill and Weston, 2001), and (b) increase the likelihood of downstream eutrophication (Tundisi, 1990). Data on the effect of selective tropical forestry on catchment-scale nutrient flux in natural forests are, however, restricted to a very few studies. The most rigorous of these were the studies undertaken within the Bukit Berembun catchments in Peninsular Malaysia (Yusop, 1989) and a 6.2 ha catchment in the Mabura Hill area of Guyana (Brouwer, 1996). Pertinent data are also available from the treatments applied to the West Creek Catchment, Surinam (Poels, 1987) and the Baru Catchment, East Malaysia (Douglas *et al.*, 1992). The plot-scale work of van Dam (2001) in Guyana, and the detailed nutrient budget for the already disturbed Bukit Tarek catchment in Peninsular Malaysia (Yusop, 1996) provide further insight into the likely processes of change.

Harvesting year impacts

The Bukit Berembun study demonstrates that during the year of timber harvesting, the flux of river-dissolved macro-nutrients (nitrate, phosphate, potassium, calcium and magnesium) increase by 1.7 to 5.6-fold where conventional selective logging is practised, and by 1.2 to 2.1-fold where 'closely-supervised / RIL' techniques are practised (Table 20.3). The process studies of van Dam (2001) in selectively logged Guyanan rainforest indicate that the accelerated nutrient flux results from (i) an increase in the amount of 'percolation water', (ii) a decrease in the nutrient uptake by the vegetation remaining in canopy gaps, and (iii) an increase in the amount of decomposable nutrients contained in the crowns of felled trees.

If the change in the losses associated with the enhanced suspended-sediment flows (and other non-dissolved losses) are taken into account, then the change in the total flux of nutrients may be a little greater. Working in the Bukit Tarek Catchments also in Peninsular Malaysia, Yusop (1996) demonstrated that only 2 to 19% of the macro-nutrient load was in the form of non-dissolved material. However, it should be noted that these catchments were selectively-logged 40 years prior to his study so that the rates of

Table 20.3. *Accelerated macro-nutrient flux from the Bukit Berembun rivers following selective timber harvesting*

Catchment (harvesting method)	Harvesting year (1 July 1983–30 June 1984)	3-year 'recovery' period (1 July 1984–30 June 1987)
C1	+ 5.6-fold NO_3[b,c]	+ 2.0-fold NO_3
(commercial)[a]	+ 3.0-fold PO_4	+ 2.3-fold PO_4
	+ 2.4-fold K^+	+ 2.1-fold K^+
	+ 1.8-fold Ca^{2+}	+ 1.8-fold Ca^{2+}
	+ 1.7-fold Mg^{2+}	+ 1.8-fold Mg^{2+}
C3	+ 2.1-fold NO_3	+ 1.6-fold NO_3
(closely supervised)[a]	+ 1.2-fold PO_4	+ 1.5-fold PO_4
	+ 1.3-fold K^{2+}	+ 1.2-fold K^{2+}
	+ 1.3-fold Ca^{2+}	+ 1.2-fold Ca^{2+}
	+ 1.4-fold Mg^{2+}	+ 1.1-fold Mg^{2+}

[a] 'Commercial logging' is also known as 'conventional' or 'unsupervised' selective logging, while 'closely supervised logging' is also known as 'reducted-impact logging (RIL)'.

[b] Macro-nutrient flux is equivalent to nutrient load.

[c] Increase in the flow of dissolved macro-nutrients (nitrate, phosphate, potassium, calcium and magnesium) over the Bukit Berembun river gauging structures within C1 and C3 relative to that in C2, the control catchment. Some bias may be incorporated due to natural differences between the control and other catchments.

sediment delivery are likely to be much less than from a period of forest harvesting. An additional source of uncertainty in the rates of change of nutrient flux is the presence of subsurface nutrient flows across catchment divides defined only by surface topography (Bruijnzeel, 1991). The small size of the Bukit Berembun C1 catchment (0.133 km^2) and the possible presence of preferential flow within the weathered granite bedrock makes such inter-basin nutrient flows a possibility (cf. earlier discussion on C2 lowflows.)

The much shorter nutrient records from a 6.2 ha catchment in the Mabura Hill area of Guyana gave a doubling of potassium and nitrate flux directly after the light selective harvesting (21 m^3 ha^{-1} : Brouwer, 1996). This change is broadly consistent with those observed for the Bukit Berembun catchments. In some contrast, however, a clear change in the phosphorous, calcium and magnesium losses could not be observed at Mabura Hill. Reported rates of acceleration of nutrient loss for the West Creek Catchment, Surinam, in the year affected by a 'refinement process' were similarly more modest than those for the harvesting year at Bukit Berembun. A 0.29-fold increase in potassium load, a 0.15-fold increase in calcium load and a 0.07-fold increase in magnesium was observed at West Creek (Poels, 1987). These data are, however, much more uncertain, given that (a) a paired catchment approach was used without calibration, (b) water-flows were assumed to be unaltered by the forestry, and (c) the disturbance process was one of 'refinement' (a process that involved the cutting of lianas and poisoning of non-commercial trees) of an already selectively-logged forest, rather than one of selective logging of virgin forest (Bruijnzeel, 1992).

Recovery

During the harvesting year in Bukit Berembun, it is the nitrate losses via riverflow that increase the most. These accelerated nitrate losses do, however, return to near natural conditions within six months of the cessation of the harvesting activities (Table 20.4 column 6) (Yusop, 1989). The other nutrients took between three and five years to return to conditions where nutrient flux was only slightly elevated above the natural condition (Table 20.4). Such rapid recovery of the nutrient losses indicates a catchment with a high 'ecosystem resilience' (Swank, 1988), with accelerating biological processes rapidly utilising the additional nutrients released to soil-water (Prof. R. Jones, pers. comm.). Further, it is interesting to note that clearfelling and burning of already selectively-logged forest in East Malaysia resulted in a similarly fast rate of recovery in the rates of catchment-scale leaching (Malmer and Grip, 1994).

The long-term inputs of macro-nutrients into the subsurface waters of a catchment derive from within (above canopy) rainfall and the weathering of soil and rock. Comparison of these 'natural rates' of input with (a) the loss of catchment nutrients in hauled timber, and (b) via the accelerated export of nutrients in riverflow (Table 20.4) demonstrates that it is the losses in timber that have the most significant impact on catchment fertility. Yet, quantification of the nutrient content of all of the timber removed from a river

Table 20.4. *Natural rates of input of macro-nutrients into subsurface water, export in harvested timber and additional mass of macro-nutrient flux from the Bukit Berembun rivers following selective timber harvesting*

Catchment (harvesting method)[a]	Input: natural rates of new nutrient delivery to sub-surface water (in rainfall and by natural weathering)[b]	Export in harvested timber[c]	Additional export in riverflow during harvesting year[d] (1 July 1983–30 June 1984)	Additional export in riverflow during 'recovery' period[d] (1 July 1984–30 June 1987)	Recovery rate[e]	C1 vs. C3 (recovery period)[f]
C1	11 kg N-total ha^{-1} yr^{-1}	–	+ 2.0 kg NO_3 ha^{-1} yr^{-1}	+ 0.4 kg NO_3 ha^{-1} yr^{-1}	0.8	+ 1.6 fold
(commercial)	0.4 kg P ha^{-1} yr^{-1}	–	+ 0.21 kg PO_4 ha^{-1} yr^{-1}	+ 0.1 PO_4 ha^{-1} yr^{-1}	0.5	+ 2.5 fold
	19 kg K^+ ha^{-1} yr^{-1}	200 kg K^+ ha^{-1}	+ 14.5 kg K^+ ha^{-1} yr^{-1}	+ 12.1 kg K^+ ha^{-1} yr^{-1}	0.2	+ 5.8 fold
	15 kg Ca^{2+} ha^{-1} yr^{-1}	45 kg Ca^{2+} ha^{-1}	+ 5.0 kg Ca^{2+} ha^{-1} yr^{-1}	+ 5.2 kg Ca^{2+} ha^{-1} yr^{-1}	−0.04	+ 4.3 fold
	9 kg Mg^{2+} ha^{-1} yr^{-1}	20 kg Mg^{2+} ha^{-1}	+ 1.8 kg Mg^{2+} ha^{-1} yr^{-1}	+ 2.5 kg Mg^{2+} ha^{-1} yr^{-1}	−0.4	+ 12.5 fold
C3	11 kg N-total ha^{-1} yr^{-1}	–	+ 0.53 kg $NO_3{}^1$ ha^{-1} yr^{-1}	+ 0.25 kg NO_3 ha^{-1} yr^{-1}	0.5	
(closely supervised)	0.4 kg P ha^{-1} yr^{-1}	–	+ 0.04 kg PO_4 ha^{-1} yr^{-1}	+ 0.04 kg PO_4 ha^{-1} yr^{-1}	0.0	
	19 kg K^+ ha^{-1} yr^{-1}	165 kg K^+ ha^{-1}	+ 2.8 kg K^+ ha^{-1} yr^{-1}	+ 2.5 kg K^+ ha^{-1} yr^{-1}	0.1	
	15 kg Ca^{2+} ha^{-1} yr^{-1}	37 kg Ca^{2+} ha^{-1}	+ 1.8 kg Ca^{2+} ha^{-1} yr^{-1}	+ 1.2 kg Ca^{2+} ha^{-1} yr^{-1}	0.3	
	9 kg Mg^{2+} ha^{-1} yr^{-1}	16 kg Mg^{2+} ha^{-1}	+ 1.2 kg Mg^{2+} ha^{-1} yr^{-1}	+ 0.2 kg Mg^{2+} ha^{-1} yr^{-1}	0.8	

[a] 'Commercial logging' is also known as as 'conventional' or 'unsupervised' selective logging, while 'closely supervised logging' is also known as 'Reduced-impact Logging (RIL)'.

[b] Rates from Table 20.2 in Bruijnzeel (1992), where the rate of 'natural weathering' is the long-term average rate of nutrient export in riverflow under natural conditions minus the long-term average rate of nutrient input from (above-canopy) rainfall.

[c] Masses from Bruijnzeel (1995).

[d] Rates from Yusop (pers. comm.).

[e] An index of the rate of improvement post the harvesting period relative to the additional losses in the harvesting period. Calculated from: *(additional export in riverflow during harvesting period – additional export in riverflow during 'recovery' period) / additional export in riverflow during harvesting period*. A larger positive number indicates a more rapid recovery from the impact experienced during the harvesting year, while a larger negative value indicates even greater losses during the 'recovery' period in comparison to the harvesting period.

[f] Impact in 'recovery period' of commercial (unsupervised) harvesting versus closely supervised (RIL) harvesting. Calculated from: *(additional export in riverflow during 'recovery' period in C1) / additional export in riverflow during 'recovery' period in C3*.

catchment or harvesting coupe is perhaps even more uncertain than quantifying accelerated nutrient flux in rivers (Table 20.4) (Nykvist, 1994).

Research needs

It is clear that there is a particularly acute dearth of studies on the selective forestry impacts on catchment-scale nutrient export. Further nutrient sampling programmes within existing (or new) catchments is, therefore, important (Bruijnzeel, 1989b). The rate of longer-term (i.e. 5–30 years) biochemical recovery, and hence the true ecological sustainability of the forestry practices adopted, can be estimated only roughly from short-term studies (Yusop, 1996), and would benefit from long-term sampling programmes, such as those at the Coweeta Experimental Watershed, in southeast USA (cf. Swank, 1988).

The rate of catchment-scale nutrient flux is controlled more by variations in the waterflow than in the nutrient concentration (Swank, 1988). Indeed, within undisturbed forest catchments, the annual fluctuations in the nutrient export are correlated strongly with (a) the proportion of rainfall-generating discharge, and (b) the discharge. As a result, separating relatively small but long-term accelerated rates of nutrient loss (by catchments affected by selective forestry) from the natural cycles in nutrient flux is very difficult. New studies that combine the modelling of cycles and trends in rainfall – runoff behaviour with those in nutrient behaviour (e.g. Eshleman, 2000), should more accurately quantify longer-term impacts on nutrient flux related to selective forestry operations.

SEDIMENT FLOWS

Several reviews indicate that the spatial and temporal variation in annual, net sediment flux for large tropical catchments could be as large as three to four orders of magnitude (Douglas, 1996; Milliman *et al.*, 1999; Walling and Webb, 1983). Depending on what are the dominant controlling factors, this may indicate that catchment sediment flows are sensitive to terrain disturbance during forestry or with other land-use activities. As discussed by Douglas and Guyot elsewhere in this volume, the factors controlling the rate of soil detachment, sediment flux and deposition include: (1) the local relief, properties of the soil and rock materials and the presence of tectonic activity, (2) the Intensity-Duration-Frequency (IDF) characteristics of the rainfall and the presence of marked cyclical behaviour, and (3) anthropogenic disturbance to the soil/rock and vegetation cover during forestry or other activities. Clearly, the relative impact of different selective forestry operations within natural forest need to be measured against the variations expected between different relief-geology and climatic regimes within the tropics. Additionally, the impact of each selective forestry practice may differ between contrasting geological and/or climatic settings.

Relief and geological controls

Walling and Webb (1983) reviewed sediment delivery data from almost 1,500 large catchments across the globe. These analyses indicate that the highest rates of erosion and sediment delivery in the tropics ($>$1,000 t km^2 yr^{-1}) occur in (i) the Cordilera Central-Andes range of South America, (ii) Taiwan Island (China), (iii) the Hongha catchment (northern Vietnam), (iv) Java Island (Indonesia), and (v) the Aure catchment (Papua New Guinea). Steep slopes are an important factor in Cordilera Central-Andes mountains, Papua New Guinea and Java (Walling and Webb, 1983; Pickup *et al.*, 1981), and the dominance of Andosols derived from pyroclastic parent materials is also important in Java (see also Hardjowitjitro, 1981). The lowest rates of erosion and sediment delivery in the tropics ($<$50 t km^2 yr^{-1}), as mapped by Walling and Webb (1983), cover (i) the Congo catchment (Central Africa), and (ii) the north-western and southern headwaters of the Amazonian basin. These regions are dominated by stable Ferralsol soils and have relatively low relief (see also Douglas and Guyot, this volume).

Rainfall regime controls

On a global basis, the annual rainfall total is of lesser importance in determining the spatial patterns of erosion and sediment delivery than is the relief-geological control (Walling and Webb, 1983 p80). Rainfall is, however, critical to the understanding of the temporal variability in tropical erosion and sediment delivery, with extreme rainfall events often being responsible for most of the sediment flows. For example, the five largest storms during 1987–9, generated 45 and 54% of the suspended-sediment flux in the 19.9 km^2 Batangsi and 12.5 km^2 Chongkak catchments, respectively, in Peninsular Malaysia (Lai, 1992). Similarly, a single storm event on the 19 January 1996 mobilised 43% of the suspended-sediment flux over the period 1 July 1995 to 30 June 1996 from the 0.44 km^2 Baru catchment in East Malaysia (Chappell *et al.*, 1999a). The impact of extreme events are also observed over significantly larger space and time scales. For example, the eight-year records for the 721 km^2 Ulu Segama catchment, gauged close to the Baru catchment, show that extreme storms occurring on only six separate days (or 0.2% of the time-series), mobilised 25% of the suspended-sediment (Douglas *et al.*, 1999). Extreme events are important to erosion and sediment delivery within the tropics (and elsewhere) because they (i) trigger new mass movements along channels (Balamurgan, 1997) and on slopes (Chappell *et al.*, 1999a, b; Larsen and Torres-Sanchez, 1998), (ii) markedly expand the contributing areas of sediments

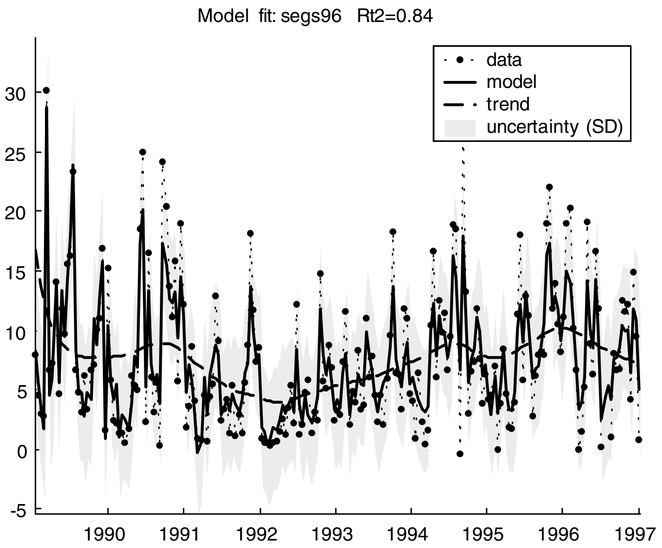

Figure 20.6 Results of the DHR modelling of the daily values of suspended-sediment concentration generated by the 721 km^2 Ulu Segama catchment against the measured data (both in rainfall equivalents).

mobilised by surfacial erosion (Croke *et al.*, 1999), and mobilise channel-bed sediments (Swanston and Swanson, 1976).

In addition to the sediment time-series being punctuated by the effects of extreme events, the impacts of cyclicity in tropical rainfall may be observed. Given that the sediment is mobilised by rainfall, greater sediment delivery would be expected during peaks in these cycles. To illustrate this effect, the daily suspended-sediment records for the 721 km^2 Ulu Segama catchment, East Malaysia (Ian Douglas, pers. comm.) are analysed using the Dynamic Harmonic Regression (DHR) model. This model is a recursive interpolation, extrapolation and smoothing algorithm for non-stationary time-series, and identifies three components in the time-series: (i) the trend, which includes inter-annual cyclicity and longer-term drifts, (ii) the within-year cycles or 'seasonality', and (iii) white noise (see Appendix). For this analysis, the relative magnitude of the cyclicity and drift dynamics in the daily suspended-sediment concentration and flux (1989–97) are compared with those in the daily rainfall records (1986–98) monitored at the DVFC meteorological station within the Ulu Segama catchment. It is important to know whether seasonal and/or inter-annual, cyclical phenomena such as the El Niño Southern Oscillation (ENSO), often observed within tropical rainfall records, are damped or magnified in the sediment records. The suspended-sediment concentration and flux data were, therefore, linearly scaled to the mean of the rainfall drift.

Application of models to the rainfall, suspended-sediment concentration and suspended-sediment flux for the Ulu Segama river produced model efficiencies (sensu. Nash and Sutcliffe, 1970) of 80%, 84% and 83%, respectively. Figure 20.6 shows the model of the suspended-sediment concentration plotted with the measured data.

The modelling indicates that the rainfall records monitored at the DVFC meteorological station exhibit marked cyclical behaviour (Figure 20.7) about the mean rainfall of 7.4 mm day^{-1}. The within-year or 'seasonal' components of this cyclicity, amounting to about 3 to 5 mm day^{-1} (Figure 20.7a), are dominated by 12 and 1 month cycles (see Bidin, 2001; Chappell *et al.*, 2001). The inter-annual cyclicity within the relatively short records for DVFC amounts to about 2 mm day^{-1} and has a periodicity of about five years (Figure 20.7b), which is coincident with the El Niño Southern Oscillation within the region (Chappell *et al.*, 2001). The variations in the longer-term drift over the 1986–98 period are not statistically significant (Figure 20.7c).

Like the rainfall, the within-year cyclicity in the records of the suspended-sediment concentration and flux are dominated by 12 and 1 month cycles, however, the strength of the cyclicity is magnified, being 5 to 20 mm day^{-1} rainfall equivalents in the case of the suspended-sediment flux. (Figure 20.7d). The inter-annual cyclicity, presumably related to short-term ENSO behaviour, is also magnified in the suspended-sediment behaviour, having a magnitude of about 4 mm day^{-1} (Figure 20.7e). Figure 20.7f shows that the longer-term drift component of the suspended-sediment flux increases slightly post-1992. While the monitoring period is still too short (1989–97) to be conclusive, the increasing drift in suspended-sediment flux may be a physical phenomenon, given that a 16 km^2 downstream area of the 721 km^2 Ulu Segama catchment was selectively-logged (with a timber yield of 103 m^3 ha^{-1}) by RIL techniques in 1993 (Greer *et al.*, 1996; Pinard *et al.*, 1995). This short period of forestry activity within the catchment was some years after the selective logging of the headwaters of the Ulu Segama in the 1970s (Greer *et al.*, 1996), and so may have punctuated the recovery from the earlier activity.

Magnification of the cyclicity means that the effects of seasonality and ENSO phenomena have a much greater impact on annual sediment budgets than would be expected from the dynamics in the rainfall. As a consequence, quantification of the impact of different selective forestry operations on the sediment yield becomes strongly dependant on the season and position within the ENSO cycle that the operations take place. Road construction and harvesting conducted within the peak of the short-term ENSO cycle (La Niña period) would be expected to have a greater relative impact on the sediment delivery compared to the same operations taking place within the ENSO trough (El Niño period).

The Baru Catchment, just downstream of the gauged 721 km^2 Ulu Segama watershed, East Malaysia, was disturbed by selective forestry between August 1988 to June 1989 which was coincident with an ENSO peak. The catchment generated a 5.3-fold increase in suspended-sediment delivery (1,600 t km^{-2} yr^{-1} versus

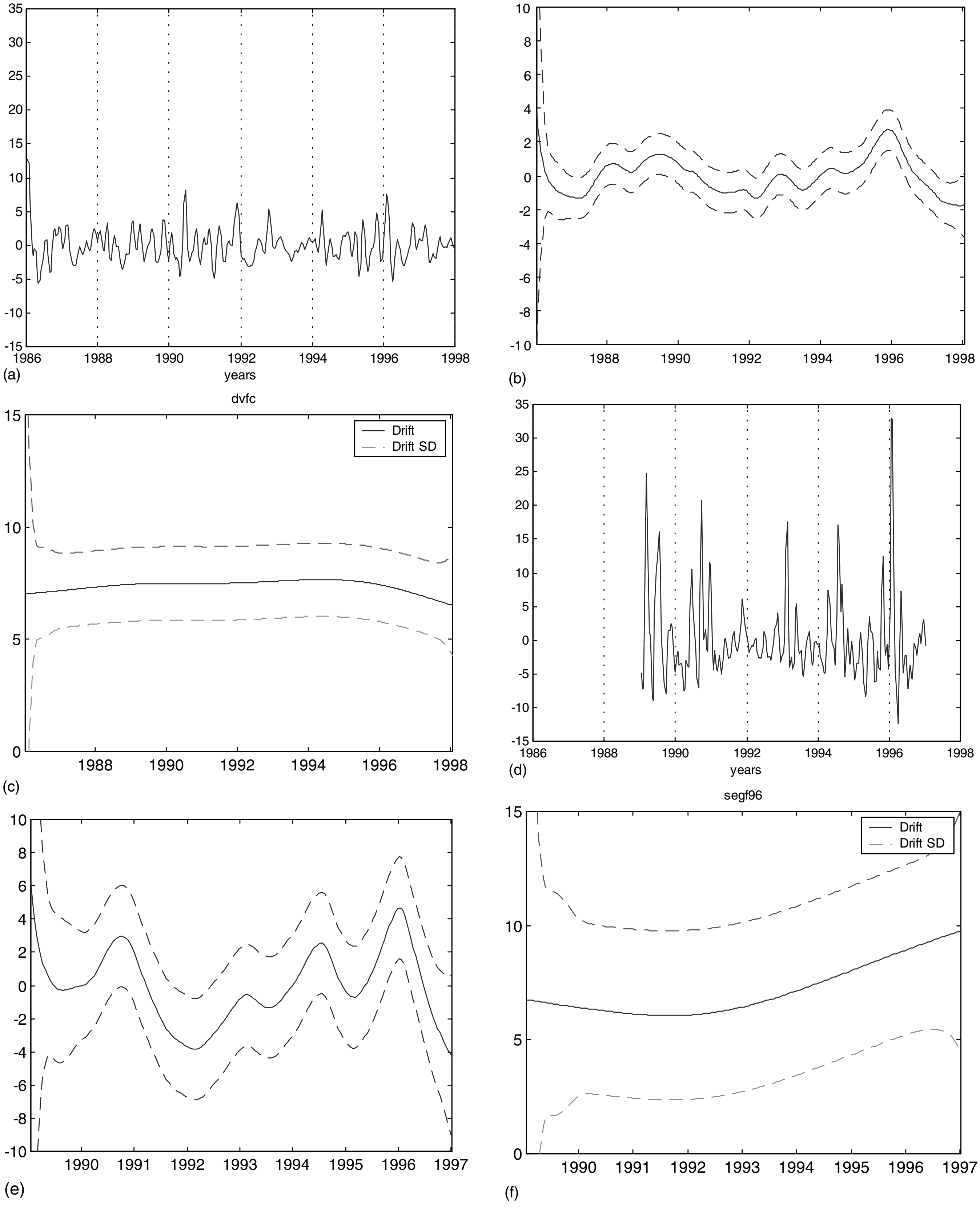

Figure 20.7 Results of the DHR modelling of rainfall and sediment trend and cycles in the Ulu Segama region of Sabah, Malaysia. (a) Seasonal cyclicity in the daily rainfalls (mm d^{-1}) at the DVFC meteorological station, Sabah, Malaysia. (b) Inter-annual cyclicity in the DVFC rainfall (mm d^{-1}). (c) Inter-annual drift in the DVFC rainfall (mm d^{-1}). (d) Seasonal cyclicity in the daily flux of suspended-sediment (in mm d^{-1} rainfall equivalents) generated by the 721 km^2 Ulu Segama catchment. (e) Inter-annual cyclicity in the daily flux of suspended-sediment (in mm d^{-1} rainfall equivalents). (f) Inter-annual drift in the daily flux of suspended-sediment (in mm d^{-1} rainfall equivalents).

Table 20.5. *Selective natural forestry impacts on catchment-scale suspended-sediment delivery*

Study number	1	2	3	4
Key reference(s)	Douglas *et al.* (1992), and Greer *et al.* (1996)	Douglas and Bidin (1994)	Lai (1992)	Lai *et al.* (1999)
Name	Baru	Jauh	Batangsi and Chongkak	Lawing
Size (km^2)	0.44	1.5	19.9 and12.7	4.7
Location	Sabah, Malaysian Borneo	Sabah, Malaysian Borneo	Peninsular Malaysia	Peninsular Malaysia
Forest type	Lowland dipterocarp	Lowland / hill dipterocarp	Hill dipterocarp	Hill dipterocarp
Relief	14–260 m, undulating	125–725 m, steep	1082 and 1265 m relief, steep	1210 m relief, steep
Slope	8°	16°	22° and 23°	24°
Geology	Siltstone / sandstone	Serpentinite	Granite and granodiorite	Granite
Rainfall regime	Equatorial	Equatorial	Equatorial	Equatorial
Practice	Conventional	Reduced-impact logging	Conventional	–
Timber yield	80 $m^3\ ha^{-1}$ (coupe 89)[a]	–	–	–
Forestry period	1988–1989	Apr–May 1992	1985– and 1944–	1993
Sediment components[b]	Suspended only	Suspended only	Suspended only	Suspended only
Forestry active period:				
Record year(s)	1988–89	May 1992 –Nov 1993	1987–9 and 1987–8	1994
Disturbed (and control) ($t\ km^{-2}\ yr^{-1}$)	1600 (300)	431 (100)	2826 and 2476 (54)	1389 (–)
Difference	5.3-fold greater	4.3-fold greater	52- and 46-fold greater	20-fold greater
Recovery period:				
Record year(s)	1993	–	–	–
Disturbed (and control) ($t\ km^{-2}\ yr^{-1}$)	283 (38)	–	–	–
Difference	7.5 fold greater	–	–	–

[a] Hamzah Tangki, pers. comm.

[b] The sediment rating approach of Gilmour (1977) indicated that a partial cut of the 0.183 km^2 North Creek catchment (Queensland, Australia) increased the suspended sediment flux by 2-fold.

300 $t\ km^{-2}\ yr^{-1}$) during that forestry period in comparison with the nearby control catchment (Table 20.5) (Douglas *et al.*, 1992). Another nearby catchment, the 1.5 km^2 Jauh, was selectively harvested in the relatively dry period of 1992. This catchment generated a slightly smaller, 4.3-fold, increase in suspended-sediment delivery (431 $t\ km^{-2}\ yr^{-1}$ versus 100 $t\ km^{-2}\ yr^{-1}$) (Table 20.5) during that period compared with the Rafflesia control catchment (Douglas and Bidin, 1994). While timing of the logging activities in the ENSO rainfall cycle between these two catchments may account for part of the small difference in the rate of accelerated sediment delivery, unfortunately, the catchments differ in two other important aspects. First, the Baru Catchment is within a region of highly unstable Alisol soils (Chappell *et al.*, 1999b) with landsliding being present even on undisturbed slopes. In contrast, the Jauh catchment has steep, but very thin, mountain soils which after some initial erosion of road surfaces leave resistant, Serpentinite rock surfaces (K. Bidin, pers. comm.). Secondly, while the Baru Catchment was managed by conventional, selective techniques, forestry in the Jauh catchment was by RIL methods which reduced the extent of haulage roads and skid trails, involved careful supervision of buffer zones, and gazetted large tracts of the catchment as too steep for logging (Douglas and Bidin, 1994; K. Bidin, pers. comm.; Douglas *et al.*, 1999). As a consequence, the difference in selective forestry impact may be related to the natural climatic cycles, relief-geology or selective forestry operations, or a combination of all three factors. Indeed, such a complex, equifinite situation was observed with a ‘partial-clearfell’ forestry study in a montane region of Puerto Rico (Larsen *et al.*, 1997).

Forestry land-use controls

Generalisation of the catchment-scale impacts of different practices of selective logging of tropical natural forests is very difficult given the dearth of experimental studies, and the effects of variations in the relief/geology and rainfall controls just described. The authors are aware of only four studies addressing catchment-scale, selective logging impacts on natural forests, and these were all undertaken within the same tropical country (Table 20.5). These studies indicate that the delivery of suspended-sediments may increase by 2–50-fold in the periods of road construction and selective timber harvesting. Douglas *et al.* (1992) and Chappell *et al.* (unpublished data) have suggested that selective forestry operations generate new sediment sources, notably road gullies, rain-splash and surficial wash on haulage roads and skidder-vehicle trails, collapses along streams (particularly at road crossings), landslides in cleared areas, landslides in road-cut materials, and soil piping under roads. The limited catchment-scale data available (Table 20.5) makes more precise quantification of the 10-fold range un-realistic, making the need for new studies to quantify which sediment sources make up most of the changes to catchment-scale sediment flux most acute (Bruijnzeel, 1996). A key issue that needs to be addressed at the catchment scale is the degree to which RIL methods lessen the physical impacts seen with conventional, unsupervised methods of selective forestry.

A further, often overlooked issue (see Douglas and Guyot, this volume), is the contribution of bedload to the total sediment budget. During the 1987–89 period, bedload accounted for an additional 1,367 and 1.6 t km^{-2} yr^{-1} of the total sediment delivery in the selectively-logged Batangsi and Chongkak catchments, respectively, and a further 125 t km^{-2} yr^{-1} in the then undisturbed Lawing catchment (Lai, 1992). Bedload data have not been collected routinely within the two other catchments (Baru and Jauh) listed in Table 20.5. Given the large difference in bedload delivery seen between the two disturbed catchments, Batangsi and Chongkak (with their similar relief, geology, vegetation and scale) exptrapolation of these results to catchments without such data would be unrealistic, yet the bedload component may be critical to the quantification of the forestry impacts on the total sediment delivery.

The annual suspended-sediment delivery for the 721 km^2 Ulu Segama catchment, East Malaysia, derived from daily riverflow and concentration data from 1989 to 1996, is 306 t km^{-2} yr^{-1}. This rate results from the history of selective-logging of over 400 km^2 of the southern headwaters primarily in the 1970s and a more recent harvesting of a further 16 km^2 in 1993, combined with the effects of natural ENSO rainfall cycles. As this scale contains annual logging coupes spanning tens of years and, thus, terrain at a range of stages from road construction to recovery with some persistent impacts, it probably provides a better estimate of sediment flux at larger time and space scales than do the results of small experimental catchments, such as those presented in Table 20.5. It should be remembered, however, that with increasing scale generally comes a reduction in mean channel slope and, therefore, an increase in the in-channel storage or residence time of the sediment (Dietrich and Dunne, 1978). This may damp the local effects associated with individual forest management coupes. Even with this scale effect and the more complex land-use histories of larger catchments, they do provide results that compliment those from small-scale ‘experimental catchment studies’ (Singh, 1998).

CONCLUSIONS

At the ‘field-scale’ of say 1 hectare, a high degree of heterogeneity is observed in the natural pattern of water, nutrient and sediment flows (Bidin, 2001; van Dam, 2001; Chappell *et al.*, 1999a,b), which is then further compounded by the localised nature of forest/terrain disturbance associated with all forms of selective forest management. This means that observation of statistically meaningful changes to the rates and distribution of water processes (i.e. water, nutrient and sediment flows) need to be made only after integration over the scale of at least the 0.1–50 km^2 ‘experimental catchment’.

This modelling-supported review of catchment-scale data shows that all forms of selective management of natural forests in the tropics have observable, if not always large, impacts on water yield and pathway-dynamics, nutrient leaching and sediment mobilisation. The relatively modest impacts might be summarised as: (i) catchment water-yield is increased, but by less than a factor of two, (ii) the rate of migration of rainfall through the catchment system to the river and hence the ‘river responsiveness’ may be increased, but only slightly and will be short-lived, and (iii) nutrient flows increase by a factor of one to six in the harvesting year. Larger relative change resulting from selective forest development is seen within the suspended-sediment flux, which seems to increase by a factor of 2 to 50, though the limited set of reliable data make interpretation of this wide range unrealistic. This makes it imperative that we obtain further data-series of the impacts of the various selective forestry practices (particularly those currently considered to be ‘Reduced Impact Logging’ methods) on the mobilisation of sediments (and associated loss of water quality and downstream sedimentation). Such an impact not only affects aquatic ecology but also the economic and social livelihoods of all river users.

This chapter also demonstrates that precise quantification of ecohydrological change is often difficult due large natural dynamics in the driving hydroclimatic regime, and persistence of some forestry impacts over several years. This shows that future research programmes need to observe data over perhaps 10 to 30 years, and need to use the latest modelling technologies to separate the dynamics of particular selective forestry practices (notably Reduced-Impact-Logging practices) from those of other selective

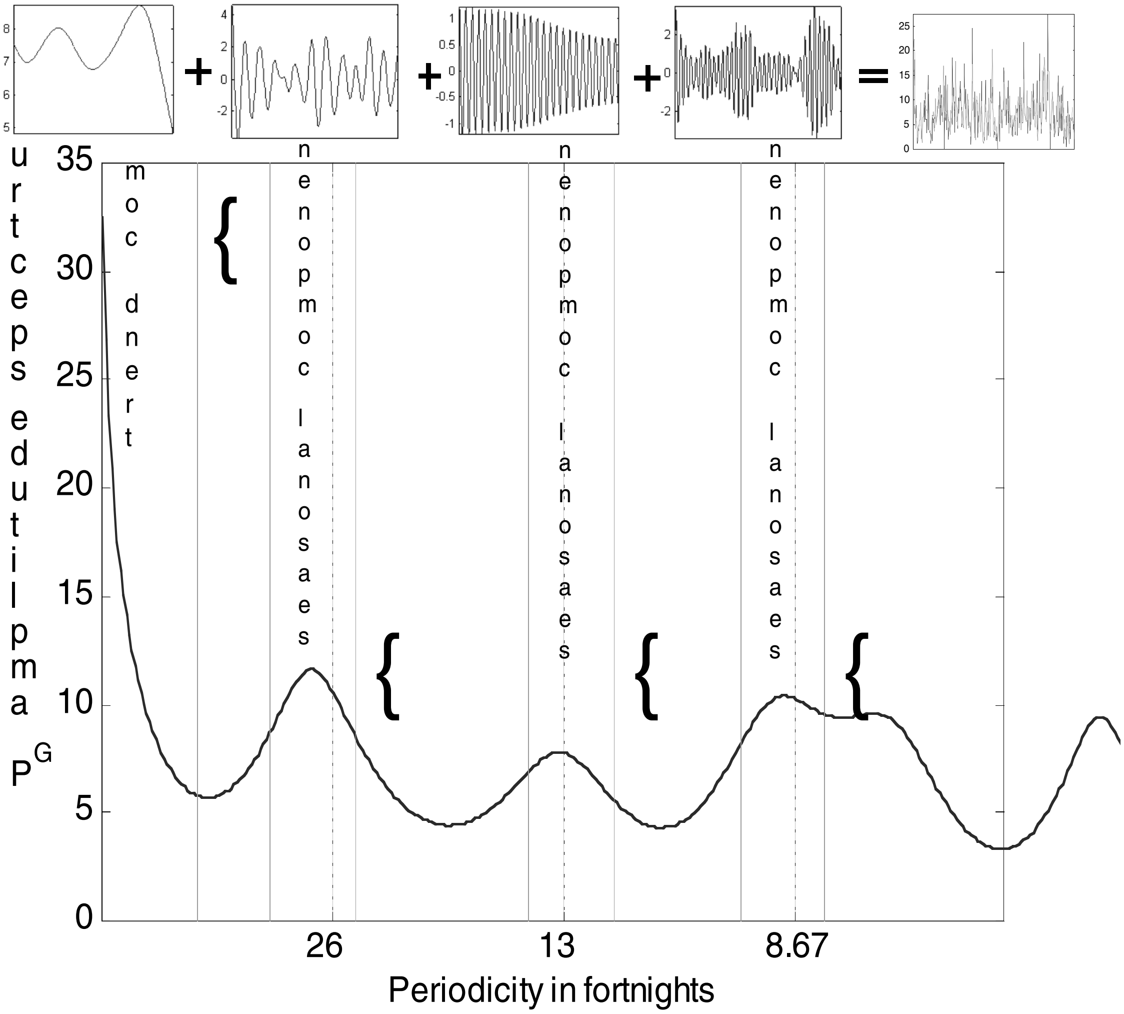

Figure 20.A1 The power spectrum and the derived trend and seasonal components of the daily rainfall time-series for the Danum Valley Field Centre, East Malaysia.

forestry activities and the spatio-temporal changes inherent in the natural system.

Maintenance of natural forests within the tropics, whether as virgin forest or selectively-managed natural forest, is important for (i) keeping drinking water abstractions free from agricultural chemicals (cf. Bolstad and Swank, 1997), and the even higher turbidity levels associated with urban construction or steepland agriculture (Douglas, 1996), (ii) the maintenance of forest flora and faunal resources, and possibly (iii) maintaining existing climatic regimes (Polcher, 1995). Many natural forests in the tropics are currently being converted or lost to agriculture, urban development and agroforestry, so that tropical rainforest research that leads to improved guidelines for the sustainable management of natural forests may provide support to those who wish to make the case to retain some of their natural forests.

APPENDIX 20.1

N. A. CHAPPELL

THE DYNAMIC HARMONIC REGRESSION MODEL

The Dynamic Harmonic Regression (DHR) model is a recursive interpolation, extrapolation and smoothing algorithm for non-stationary time-series, and identifies three components in the time-series: (i) the trend, which includes inter-annual cyclicity and longer-term drifts, (ii) the within-year cycles or 'seasonality', and (iii) the white noise, i.e.

$$SS_{(t)} = T_t + S_t + e_t \qquad (20.A1)$$

where $SS_{(t)}$ is the time-series of observed suspended-sediment flux, T_t is the trend (see Figure 20.A1) which includes the drift in long-term average suspended-sediment flux and the inter-annual cycles, S_t is the periodic component related to annual and intra-annual seasonality (see Figure 20.A1), and e_t is the white noise. The S_{t} term is further defined as:

$$S_{\mathrm{t}} = \sum_{i=1}^{R} \{a_{it} \cos(\omega_i t) + b_{it} \sin(\omega_i t)\} \tag{20.A2}$$

where $a_{i,t}$ and $b_{i,t}$ are the Time-Variable-Parameters or TVPs of the model, R is the number of seasonal components, and ω_i are the set of frequencies chosen by reference to the spectral properties of the time-series (Young, 1998; Young *et al.*, 1999). Optimisation of the TVPs is achieved by first estimating the Noise-Variance-Ratio (NVR) of the TVPs. This is achieved in the frequency domain by fitting the logarithmic pseudo-spectrum of the DHR model to the estimated logarithmic AutoRegressive (AR) spectrum of the observed rainfall series. The order of the AR model is identified via the Akaike Information Criterion. Once NVR parameters are optimised (NB these define the widths of bands of each seasonal component shown in Figure 20.A1), a single run of two recursive algorithms, the Kalman Filter and Fixed-Interval-Smoothing equations provide estimates of the various components. The estimated trend component (the first segment of the power spectrum shown in Figure 20.A1) is further split into a very slowly changing drift and the inter-annual cyclic component. Since no assumptions are made as to the periodicity of the cycle, it is unlikely that any artifacts are introduced in the procedure. Further details and examples of the DHR model are given in http://www.es.lancs.ac.uk/cres/captain.

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