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

N. A. Chappell

Lancaster University, UK

W. Tych

Lancaster University, UK

Z. Yusop

Universiti Teknologi Malaysia, Malaysia.

N.A. Rahim

Forestry Research Institute of Malaysia, Kuala Lumpur, Malaysia

B. Kasran

Forestry Research Institute of Malaysia, Kuala Lumpur, Malaysia

INTRODUCTION

Selective forestry is a set of commercial forestry practices that involve 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 been clearfelled for non-forest uses or converted to plantation or agroforestry) covers a very wide range of practices including highlead and tractor yarding, harvesting of only large, commercial trees, protection of riparian vegetation along rivers, and protection of forest on very steep hills are, however, utilised under this general management system (Conway, 1982). 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 (Bruijnzeel, 1992). 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 affecting 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 un-used 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 utilised 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 aerial extent of natural forest. For example, within South and Southeast 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).

Scale and variability

Selective forestry is managed by dividing the forestry concession into annual harvesting coupes, and these are typically 10-50 km² 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 & 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 & 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 & Torres-Sanchez, 1998) or root-anchoring properties of different plant species (Collison & 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 km² has been seen by hydrologists and geomorphologists as this fundamental scale of integration (Gregory & 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

(Bruinjzeel, 1989a; 1990; 1992; 1996; Abdul Rahim & 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 (Bruinjzeel, 1991; 1996) further limits 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, Bruinjzeel (1989a; 1991) has questioned the evapo-transpiration and nutrient budgets of many tropical catchment studies, because the authors have implicitly assumed 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 inadequately characterised 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 9-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 & 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 & 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 only over the 1 to 3 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 to assessment of 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 which has meant that forest management agencies and companies have improved the quality of their forest management records.

Given these issues, this paper will seek to: (i) assimilate the results of studies of selective forestry impacts on catchment-scale water, nutrient and

sediment flows in tropical natural forests, and (ii) 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 evapo-transpiration.

Evapo-transpiration, 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, or 'evapo-transpiration' from these bare earth surfaces are likely to be less than that 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). These ground vegetation are 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 is too limited for generalisation (Bruijnzeel, 1996; 2001; Hafkenscheid, 2000). As selective logging generates smaller gaps in the forest, where (i) new growth of pioneer trees, (ii) accelerated growth of younger and smaller commercial trees, and/or (iii) 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) have noted high rates of transpiration from vines in secondary Amazonian forest and pioneer trees in East Malaysian rainforest, respectively.

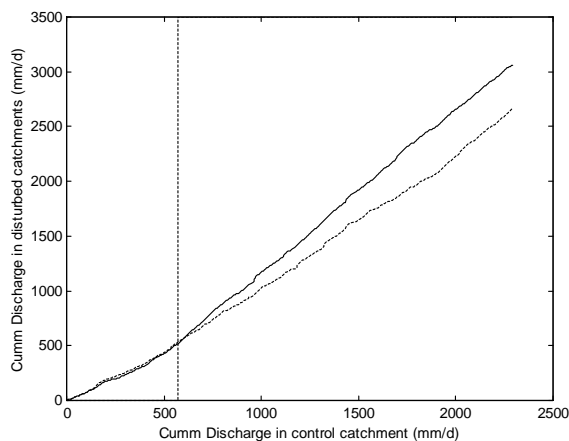


Figure 20.1. The double-mass curve of riverflows for the conventionally-logged catchment versus the control catchment (black line), and RIL catchment versus the control catchment (broken line), Bukit Berembun, Negri Sembilan, Malaysia. The vertical dashed line indicates the start of forestry activities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

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 ($2^{\circ}46' N$, $102^{\circ}6' E$) were installed within 'lowland dipterocarp rainforest' on Acrisol soils derived from a weathered granite geology (Abdul Rahim, 1990; Abdul Rahim & 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 & 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 (Fig. 20.1 [`\\wlodek\BDRIVER2.M`]). The catchment with the greater harvesting intensity (i.e., 40 % timber extraction rather than 33 %; Abdul Rahim & Harding, 1992) resulted in a greater increase in water-yield (Fig. 20.1). This selective-logging produced a gradual increase in water-yield over the initial harvesting period, in comparison to the step change in the double-mass-plot observed for the clearfelled Sungai Tekam 'Catchment A', also in Peninsular Malaysia

(see Fig. 5 in Abdul Rahim, 1988). Interestingly, the greater water-yields following selective forestry persisted over the six years of intensive monitoring after harvesting phase (Fig. 20.1). Bidin (2001) examining catchment water yield of a selectively managed forest in East Malaysia from one to eight years post disturbance, similarly failed to observe a change in the water balance with forest recovery (above 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) in comparison to 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 rainforests of South America. While not being directly applicable to the impacts of selective forestry on water balance in tropical natural forests, the partial-clearfell 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 to that of the original climax trees. Thus reduced transpiration from the greater number of canopy gaps could be an explanation for the increase in water yield following selective felling. Other plot-based work within selectively-managed forest in Indonesian Borneo, would suggest 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 neighboring Malaysian Borneo, has, however, shown that rates of wet-canopy evaporation can be greater in highly damaged patches of rainforest in comparison to the 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 more definitively apportion catchment-scale evapotranspiration into the components of transpiration and wet-canopy evaporation

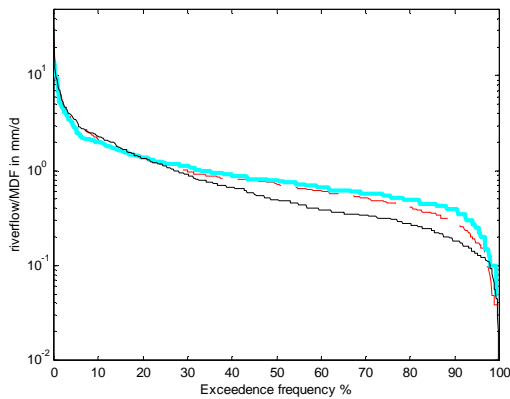


Figure 20.2. The flow-duration curves using data for the 1981-2 period for the control catchment (grey line), the conventionally-logged catchment (broken black line), and the RIL catchment (solid black line). Bukit Berembun riverflow is normalised by the mean daily flow (MDF).

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 substantial changes to the catchment water-paths result 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 in to Humic Acrisols soils in Costa Rica (Spaans *et al.*, 1990), Haplic Acrisols (Malmer & Grip, 1990) and Alisols (Van der Plas & 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 again examine the data for the Bukit Berembun catchments - prior to any forestry activities (1981-2), the three Bukit Berembun catchments have different natural flow regimes (Fig. 20.2) The C3 catchment was much more flashy prior to RIL logging in comparison to the other two catchments (Fig. 20.2). The smallest of the catchments, the 4.6 ha C2, had the greatest lowflows per unit catchment area (in relative



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).

and absolute terms) and the largest, 30.8 ha C3, had the least lowflow (Fig. 20.2). This is not expected, as water that has percolated to depth has more likelihood of returning to the ground-surface before a river gauging structure as catchment size increases up to 1 km² (Chappell *et al.*, 1999a). As the smallest catchment (C2) is only on the lower slopes of the hill that all three catchments occupy (Fig. 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 (Table 20.1). 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 Northeast India, while Gilmour (1977) failed to observe any change in peakflows during their partial-clearfell 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 is the statistic, the greater is 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) (Fig. 20.4). The undisturbed, control catchment (C2) maintained a

Table 20.1. Daily riverflow (mm/d) equalled or exceed for 10 % of the time (Q10 statistic describing highflows) within the Bukit Berembun experimental catchments.

	C1 Unsupervised 13.3 ha	C2 control logging 4.6 ha	C3 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. Q30/Q70 River flashiness statistics for the Bukit Berembun experimental catchments. Riverflows in the FDC are normalised by the respective mean daily flows (MDF)

	C1 Unsupervised 13.3 ha	C2 control logging 4.6 ha	C3 RIL 30.8 ha
Pre. Logging (1981-2)	1.9815a	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	same	slightly less
flashy		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 Q30/Q70 statistic for 1981-2 minus that for either 1984-5 or 1984-8

very similar Q30/Q70 statistic throughout the whole study period (Fig 20.4a, Table 20.2). The conventionally logged C1 catchment became slightly more flashy immediately after harvesting activities (Table 20.2), but then recovered to the pre-logging condition within a few years (Fig. 20.4b). In some contrast, the river regime within the RIL logged catchment (C3) became and remained more damped (Fig. 20.4c, Table 20.2) in comparison to 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 road surfaces with the conventionally logged C1 catchment in comparison to 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 whilst it is 0.10 km ha⁻¹ within RIL (Abdul Rahim & Harding, 1992). This may have lead to

greater quantities of rapid flowing surface flows on road surfaces or in roadside drains that would have given lightly 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, quantities of 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 adding damping to storm behaviour within rivers. While this second explanation would be consistent with the results of C1, it wouldn't be totally consistent with those of C3, so we would suggest that the mechanism of small changes to the quantities of surface flow is the more likely mechanism.

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 whole range of

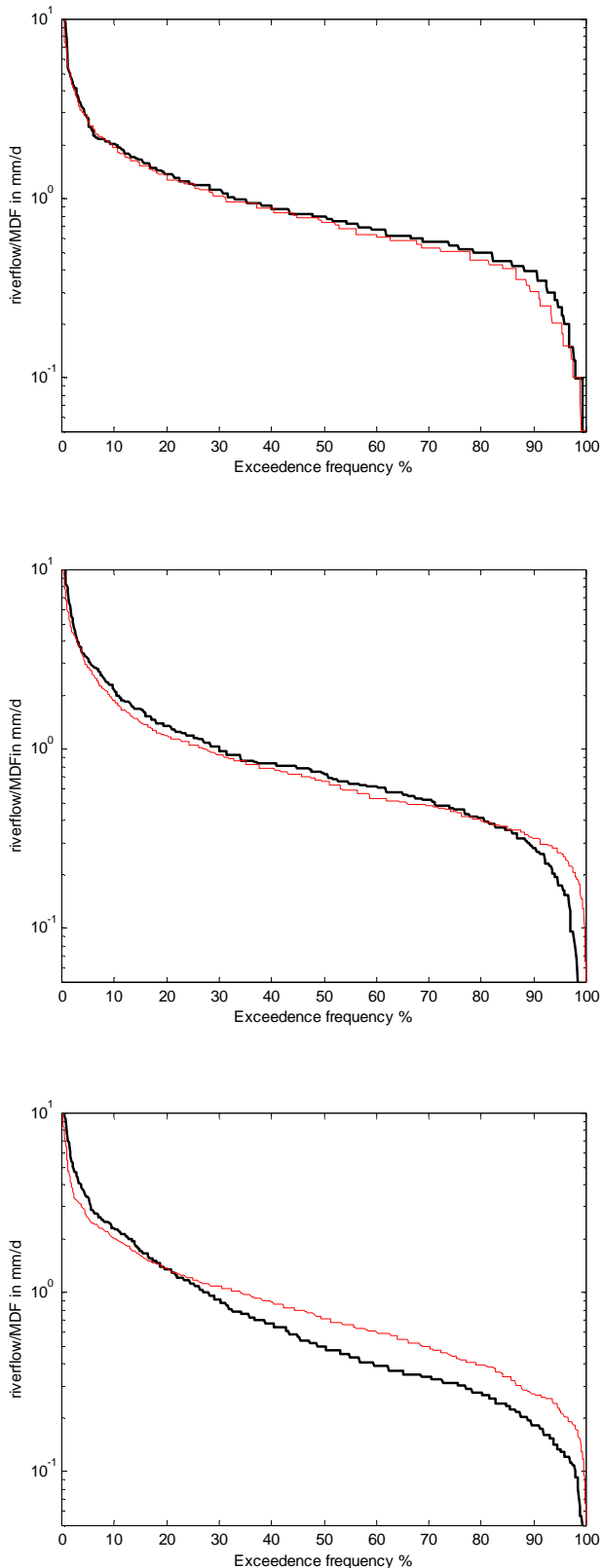


Figure 20.4. The flow-duration curves for the period 1981-2 (black line) and period 1984-5 (grey line) using riverflow data for: (a) the control catchment, (b) the conventionally-logged catchment, and (c) the RIL catchment. All Bukit Berembun data are normalised by the respective mean daily flows (MDFs).

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 & Jakeman, 1996). Any changes in these parameters following the onset of forestry may be caused by the vegetation and/or terrain modifications accompanying the forestry. Young & 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 & Hornberger (1993), is a type of 'hybrid metric-conceptual model'. Middleton (2000) provides a good introduction to modelling with transfer functions.

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 & Beven, 1994; Chappell *et al.*, 1999a; Young, 2001). Many different model structures were then utilised 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 are 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 (Fig 20.5a) and explained 89 % of the variance in the riverflow dynamics. In transfer function form of the optimal model structure was:

$$q(k) = \frac{P_0 - P_1 z^{-1} - P_2 z^{-2}}{1 - \mathfrak{R} z^{-1}} r_{eff}(k) \quad (1)$$

where $q(k)$ is the riverflow at the time index k , \mathfrak{R} is the recession or lag parameter, P_0 , P_1 and P_2 are the

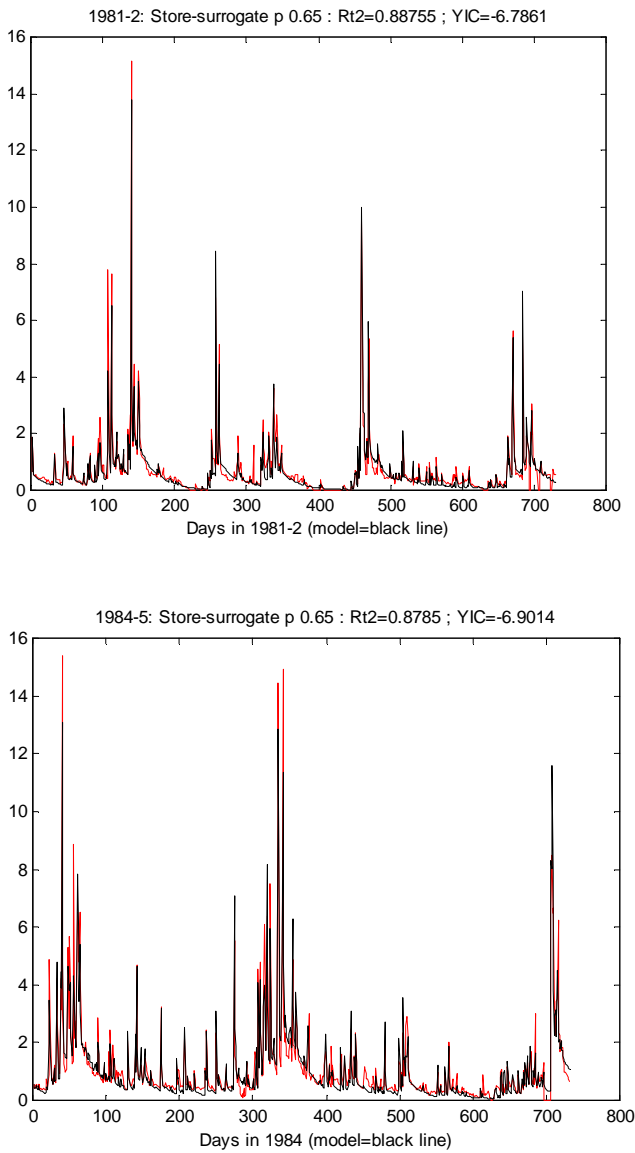


Figure 20.5. Observed (grey broken line) and simulated (black solid line) riverflow generated by the Bukit Berembun C1 catchment during: (a) 1981-2 and (b) 1984-5.

three system production or 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:

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

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

$$r_{eff}(k) = r(k) \{q(k)^\beta\}; \text{ where } \beta = 0.65 \quad (3)$$

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 β is the estimate of the power-law exponent (after Young & Beven, 1994). In order 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, is described as the 'Store-Surrogate Sub-Model', captures the non-linear effects resulting from subsurface water storage (Young & Beven, 1994; Young *et al.*, 1997), wide macropore 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 (\mathcal{R}). 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 (\mathcal{R}). The recession parameter is usually presented in terms of a time constant (TC), where:

$$TC = \frac{-t_{base}}{\log_e(-\mathcal{R})} \quad (4)$$

and t_{base} is the time-base of the data-series (i.e., a 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 23.0594 ± 0.18858 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 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 (Fig. 5b). Critically, the residence time for the logging period remained virtually

unchanged at 23.469 ± 0.16673 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 in comparison to characteristics derived from only local parts of the flow-duration-curves described earlier. We might then ask, why doesn't phenomena such as forestry road construction 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 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. com.) indicate that even where overland flow is generated on road surfaces, a significant proportion will drain onto surrounding slopes where it will infiltrate, rather than directly enter a stream channel.

Research needs

While the impact of selective forestry on water yield seems relatively small in comparison to the impact of clearfelling and conversion from natural forest (cf. Bruijnzeel, 1990; 1996; 2001), understanding the relative role of (i) changes in the transpirational losses compared to (ii) 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 accurately apportion catchment-scale evapo-transpiration 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 6 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 appeared not to give fully consistent results, though large, sustained impacts on river flashiness were not observable by either method. The small inconsistency in the interpretations may be, at least in part, 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 impact on the river hydrograph. 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 & Weston, 2001), and (b) increase the likelihood of downstream eutrophication (Tundisi, 1990). Data on the affect 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 studies were those 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 river-dissolved flux of macro-nutrients (nitrate, phosphate, potassium, calcium and magnesium) increase by 1.7 to 5.6 fold where conventional selective logging is practiced, and by 1.2 to 2.1 fold where 'closely-supervised / RIL' techniques are practiced (Table 20.3). The process studies of van Dam (2001) in selectively logged Guyanan rainforest would indicate that the accelerated nutrient flux results from (i) an increase in the amount of 'percolation water', (ii) a decrease in the

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 (commercial)a	+ 5.6 fold NO ₃ b,c + 3.0 fold PO ₄ + 2.4 fold K ⁺ + 1.8 fold Ca ²⁺ + 1.7 fold Mg ²⁺	+ 2.0 fold NO ₃ + 2.3 fold PO ₄ + 2.1 fold K ⁺ + 1.8 fold Ca ²⁺ + 1.8 fold Mg ²⁺
C3 (closely supervised) a	+ 2.1 fold NO ₃ + 1.2 fold PO ₄ + 1.3 fold K ⁺ + 1.3 fold Ca ²⁺ + 1.4 fold Mg ²⁺	+ 1.6 fold NO ₃ + 1.5 fold PO ₄ + 1.2 fold K ⁺ + 1.2 fold Ca 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 'Reduced 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.

nutrient uptake by the remaining vegetation 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 sediment delivery are likely to be much less than 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 km²) and the possible presence of preferential flow within the weathered granite bedrock makes such inter-basin nutrient flows a possibility.

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 m³ 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 are increased the most. These accelerated nitrate losses do, however, return to near natural conditions within 6-months of the cessation of the harvesting activities (Table 20.4 column 6; Yusop, 1989). The other nutrients took between 3 and 5 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 of the catchment-scale leaching rates (Malmer & Grip, 1994).

The long-term inputs of macro-nutrients into the subsurface waters of a catchment comprise of those 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

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	Additional export in riverflow during harvesting year ^c (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 (commercial)	11 kg N-total ha ⁻¹ yr ⁻¹ 0.4 kg P ha ⁻¹ yr ⁻¹ 19 kg K ⁺ ha ⁻¹ yr ⁻¹ 15 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ 9 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	- - 200 kg K ⁺ ha ⁻¹ 45 kg Ca ²⁺ ha ⁻¹ 20 kg Mg ²⁺ ha ⁻¹	+ 2.0 kg NO ₃ ha ⁻¹ yr ⁻¹ + 0.21 kg PO ₄ ha ⁻¹ yr ⁻¹ + 14.5 kg K ⁺ ha ⁻¹ yr ⁻¹ + 5.0 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ + 1.8 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	+ 0.4 kg NO ₃ ha ⁻¹ yr ⁻¹ + 0.1 kg PO ₄ ha ⁻¹ yr ⁻¹ + 12.1 kg K ⁺ ha ⁻¹ yr ⁻¹ + 5.2 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ + 2.5 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	0.8 0.5 0.2 -0.04 -0.4	+ 1.6 fold + 2.5 fold + 5.8 fold + 4.3 fold + 12.5 fold
C3 (closely supervised)	11 kg N-total ha ⁻¹ yr ⁻¹ 0.4 kg P ha ⁻¹ yr ⁻¹ 19 kg K ⁺ ha ⁻¹ yr ⁻¹ 15 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ 9 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	- - 165 kg K ⁺ ha ⁻¹ 37 kg Ca ²⁺ ha ⁻¹ 16 kg Mg ²⁺ ha ⁻¹	+ 0.53 kg NO ₃ ha ⁻¹ yr ⁻¹ + 0.04 kg PO ₄ ha ⁻¹ yr ⁻¹ + 2.8 kg K ⁺ ha ⁻¹ yr ⁻¹ + 1.8 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ + 1.2 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	+ 0.25 kg NO ₃ ha ⁻¹ yr ⁻¹ + 0.04 kg PO ₄ ha ⁻¹ yr ⁻¹ + 2.5 kg K ⁺ ha ⁻¹ yr ⁻¹ + 1.2 kg Ca ²⁺ ha ⁻¹ yr ⁻¹ + 0.2 kg Mg ²⁺ ha ⁻¹ yr ⁻¹	0.5 0.0 0.1 0.3 0.8	

^a 'Commercial logging' is also known 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.

timber removed from a river 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 at 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 only roughly estimated 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 strongly correlated 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 3 to 4 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. 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 & 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 ($> 1,000 \text{ t km}^2 \text{ yr}^{-1}$) 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 & Webb, 1983; Pickup *et al.*, 1981), and the dominance of Andosols derived from pyroclastic parent materials is also important in Java (see also Hardjowitjito, 1981). The lowest rates of erosion and sediment delivery in the tropics ($< 50 \text{ t km}^2 \text{ yr}^{-1}$), as mapped by Walling & 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.

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 & 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 19th January 1996, mobilised 43 % of the suspended-sediment flux over the period 1st July 1995 to 30th 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 8-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

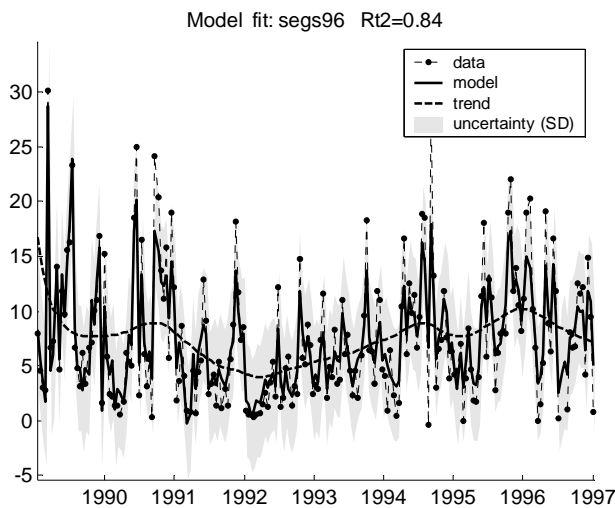


Figure 20.6. Results of the DHR modelling of the daily values of suspended-sediment concentration generated by the 721 km² Ulu Segama catchment against the measured data (both in rainfall equivalents).

within the tropics (and elsewhere) because they (i) trigger new mass movements along channels (Balamurugan, 1997) and on slopes (Chappell *et al.*, 1999ab; Larsen & Torres-Sanchez, 1998), (ii) markedly expand the contributory-areas of sediments mobilised by surficial erosion (Croke *et al.*, 1999), and mobilise channel-bed sediments (Swanston & 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 km² Ulu Segama catchment, East Malaysia (Prof. 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 (cf. Nash & Sutcliffe, 1970) of 80 %, 84 % and 83 %, respectively. Fig. 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 (Fig. 7ab [wlodek@unesco1.m]) 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 (Fig. 7a), is 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 5 years (Fig. 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 (Fig. 7c; Chappell *et al.*, 2001).

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. (Fig. 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 (Fig. 7e). Fig. 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 phenomena given that a 16 km² downstream area of the 721 km² Ulu Segama catchment was selectively-logged (with a timber yield of 103 m³ 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

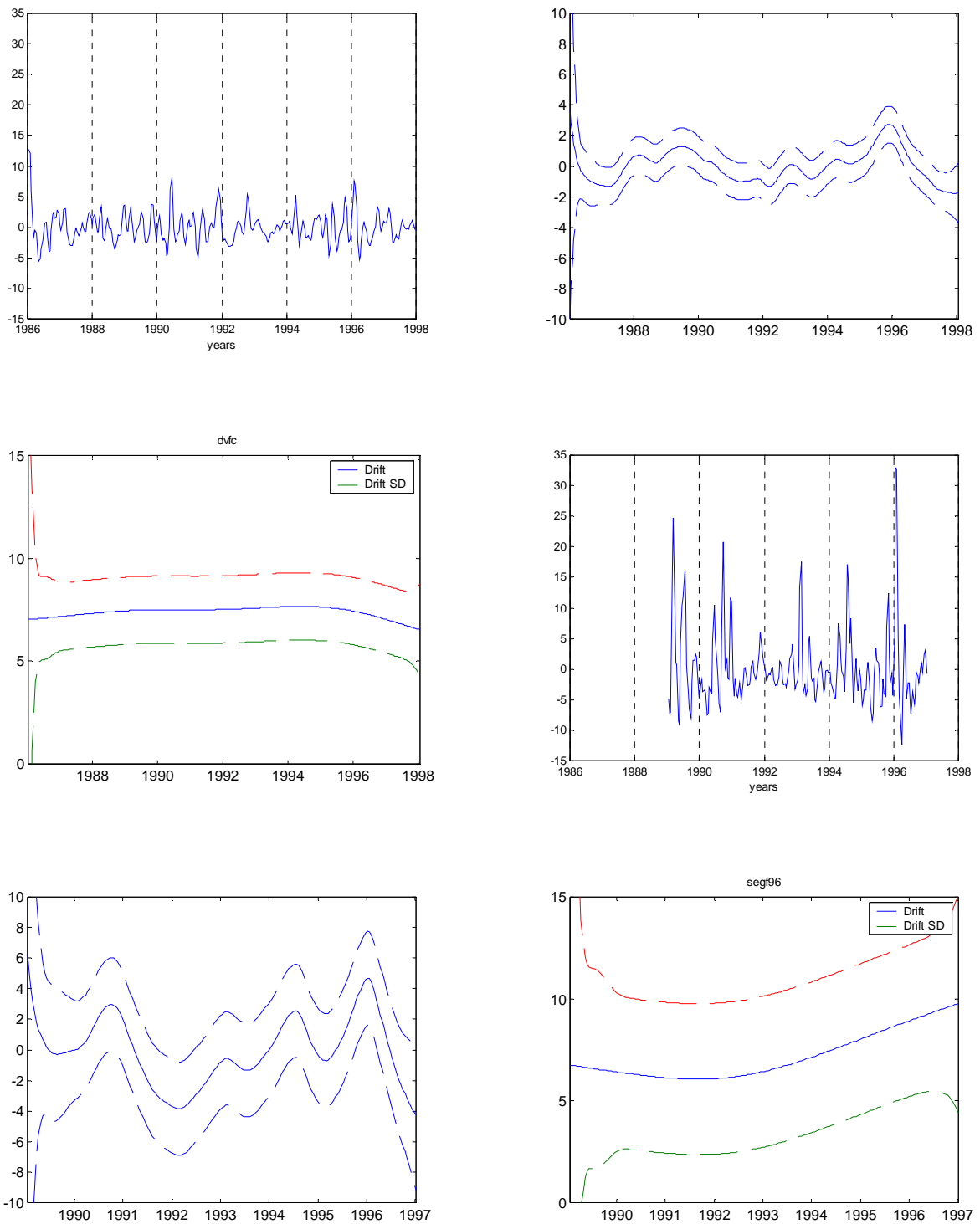


Figure 20.7. Results of the DHR modelling of rainfall and sediment trend and cycles in the Ulu Segama region of Sabah, Malaysia: (a) Seasonal cyclicity in the daily rainfalls (mm d^{-1}) at the DVFC meteorological station, Sabah, Malaysia. (b) Inter-annual cyclicity in the DVFC rainfall (mm d^{-1}), (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), and (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 <i>et al.</i> (1992) & Greer <i>et al.</i> (1996)	Douglas & Bidin (1994)	Lai (1992)	Lai <i>et al.</i> (1999)
Name	Baru	Jauh	Batangsi & Chongkak	Lawing
Size (km ²)	0.44	1.5	19.9 & 12.7	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 & 1265 m relief, steep	1210 m relief, steep
Slope	8o	16o	22o & 23o	24o
Geology	siltstone / sandstone	serpentinite	granite & granodiorite	granite
Rainfall regime	Equatorial	Equatorial	Equatorial	Equatorial
Practice	Conventional	RIL	Conventional	-
Timber yield	80 m ³ ha ⁻¹ (coupe 89)a	-	-	-
Forestry period	1988-1989	Apr-May 1992	1985- & 1944-	1993
Sediment components	suspended only	suspended only	suspended only	suspended only
<i>Forestry active period:</i>				
Record year(s)	1988-89	May '92 -Nov '93	1987-89 & 1987-88	1994
Disturbed (& control) in t km ⁻² yr ⁻¹	1,600 (300)	431 (100)	2,826 & 2,476 (54)	1,389 (-)
Difference	5.3 fold greater	4.3 fold greater	52 & 46 fold greater	20 fold greater
<i>Recovery period:</i>				
Record year(s)	1993	-	-	-
Disturbed (& control) in t km ⁻² yr ⁻¹	283 (38)	-	-	-
Difference	7.5 fold greater	-	-	-

a Hamzah Tangki, pers. comm.

NB. The sediment rating approach of Gilmour (1977) indicated that a partial cut of the 0.183 km² North Creek catchment (Queensland, Australia) increased the suspended sediment flux by 2-fold.

cycle (La Nina period) would be expected to have a greater relative impact on the sediment delivery in comparison to the same operations being taking place within the ENSO trough (El Niño period).

The Baru Catchment, just downstream of the gauged 721 km² 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 300 t km⁻² yr⁻¹) during that forestry period in comparison to the nearby control catchment (Table 20.5; Douglas *et al.*, 1992). Another nearby catchment, the 1.5 km² 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 in comparison to the Rafflesia control catchment (Douglas & 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 (Dr. 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 & Bidin, 1994; Dr. 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.* (in submission) 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 unrealistic, 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, 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 has not been routinely collected within the two other catchments (Baru and Jauh) listed within 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) extrapolation 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 km² 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 km² of the southern headwaters primarily in the 1970s and a more recent harvesting of a further 16 km² 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 of mean channel slope and, therefore, an increase in the in-channel storage or residence time of the sediment (Dietrich & 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 greatly 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.*, 1999ab), 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 km² 'experimental catchment'.

This modelling-supported review of catchment-scale data indicates 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 short-lived, and (iii) nutrient flows increase by a factor of 1 to 6 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 review further demonstrates that precise quantification of ecohydrological change is often difficult due large natural dynamics in the driving hydroclimatic regime, and persistence of some

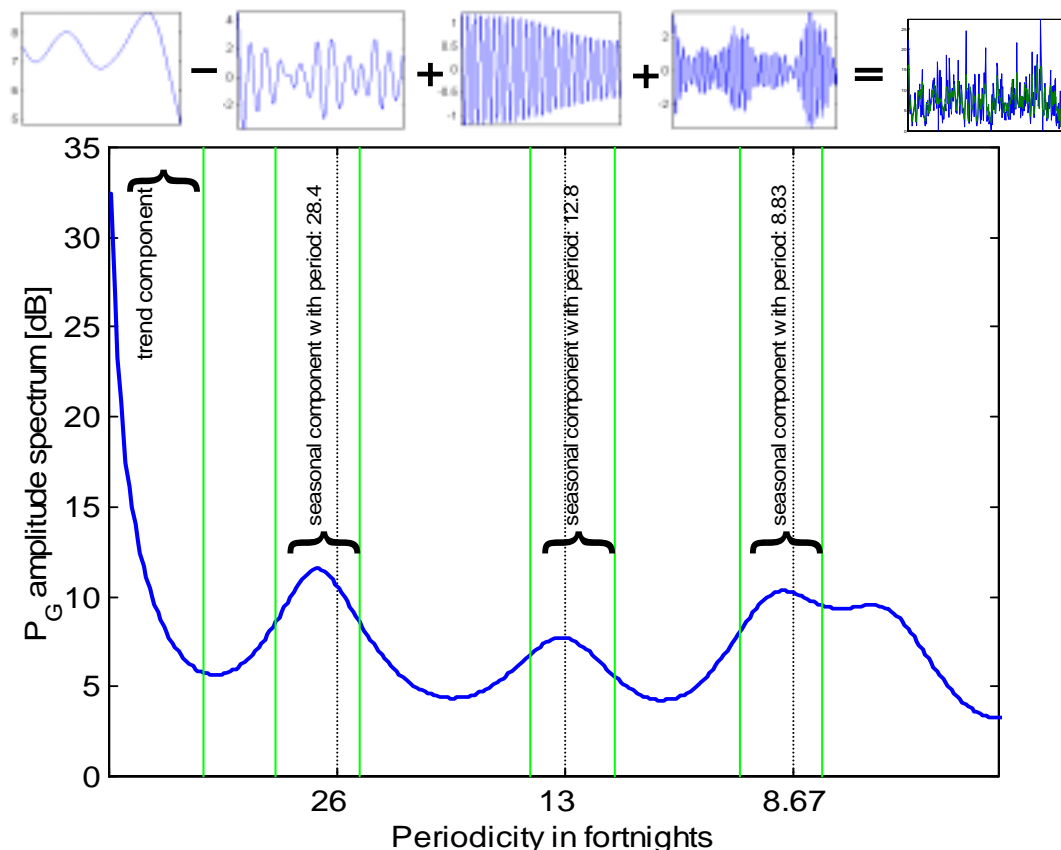


Figure 20.A1: The power spectrum and the derived trend and seasonal components of the daily rainfall time-series for the Danum Valley Field Centre, East Malaysia.

forestry impacts over several years. This would suggest that future research programmes need to observe data over perhaps 10 to 30 years, and need to utilise the latest modelling technologies to separate the dynamics of particular selective forestry practices (notably Reduced-Impact-Logging practices) from those of other selective 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 & 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 / lost to agriculture, urban development and agroforestry, so 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 cyclicality and longer-term drifts, (ii) the within-year cycles or 'seasonality', and (iii) the white noise, i.e.,

$$SS_{(t)} = T_t + S_t + e_t$$

where $SS_{(t)}$ is the time-series of observed suspended-sediment flux, T_t is the trend (see Fig. 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 Fig. 20.A1), and e_t is the white noise. The S_t term is further defined as:

$$S_t = \sum_{i=1}^R \{a_{it} \cos(\omega_i t) + b_{it} \sin(\omega_i t)\}$$

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 Fig. 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 Fig. 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>.

References

- Abdul Rahim, N. (1988). Water yield changes after forest conversion to agricultural landuse in Peninsular Malaysia. *Journal of Tropical Forest Science*, 1: 67-84.
- Abdul Rahim, N. (1990). *The effects of selective logging methods on hydrological parameters in Peninsular Malaysia*. Unpublished PhD thesis, Bangor : University of Wales.
- Abdul Rahim, N. and Harding, D.(1992). Effects of selective logging methods on water yield and streamflow parameters in Peninsular Malaysia. *Journal of Tropical Forest Science*, 5: 130-154.
- Abdul Rahim, N. *et al.*, (1997). *EIA Guidelines for harvesting of Natural Forests*. FRIM Technical Information Handbook No. 14. Kuala Lumpur : Forestry Research Institute of Malaysia.
- Abdul Rahim, N. and Zulkifli, Y. (1994). Hydrological response to selective logging in Peninsular Malaysia and its implications on watershed management. In *Proceedings of the International Symposium on Forest Hydrology*, pp. 263-274. Tokyo, Japan, October 1994..
- Adjers, G., Hadengganan, S., Kuusipalo, J., Nuryanto, K. and Vesa, L. (1995). Enrichment planting of dipterocarps in logged-over secondary forests - effect of width, direction and maintenance method of planting line on selected Shorea species. *Forest Ecology and Management*, 73: 259-270.
- Asdak, C. Jarvis, P.G., van Gardingen, P. & Fraser, A. (1998). Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia. *Journal of Hydrology*, 206: 237-244.
- Attiwill, P.M. & Weston, C.J. (2001). Forest soils. In *The Forests Handbook*, ed. J. Evans, pp157-187, Oxford: Blackwell.
- Baharuddin, K. (1995). *Effects of properties and soil erosion in a hill dipterocarp forest of Peninsular Malaysia*. Research Pamphlet No. 119. Kuala Lumpur : Forestry Research Institute of Malaysia.
- Balamurgan, G. (1997). *Suspended solids dynamics in small forested catchments in Ulu Segama, Sabah, Malaysia*. Unpublished PhD thesis, Manchester : University of Manchester.
- Becker, P. (1996). Sap flow in Bornean heath and dipterocarp forest trees during wet and dry periods. *Tree Physiology*, 16: 295-299.
- Bidin, K. (2001). Spatio-temporal variability in rainfall and wet-canopy evaporation within a small catchment recovering from selective tropical forestry. Unpublished PhD thesis. Lancaster : University of Lancaster.
- Bolstad, P.V. & Swank, W.T. (1997). Cumulative impacts of landuse on water quality in a Southern Appalachian watershed. *Journal of the American Water Resources Association*, 33: 519-533.
- Bonell, M., Gilmour, D.A., & Cassells, D.S. (1983). Runoff generation in tropical rainforests of north-east Queensland, Australia, and its implications for land use management. In *Proc. of symp. on the hydrology of humid tropical regions, IAHS Publ. 140*, ed. R. Keller, pp287-297. Paris: IAHS
- Bonell, M. & Balek, J. (1993) Recent scientific developments and research needs in hydrological processes of the humid tropics. In *Hydrology and Water Management in the Humid Tropics*, eds. M. Bonell, M.M. Hufschmidt, & J.S. Gladwell, pp. 167-260. Cambridge : Cambridge University Press.
- Brouwer, L.C. 1996. *Nutrient cycling in pristine and logged tropical rain forest*. Unpublished PhD thesis. Utrecht : Utrecht University.
- Bruijnzeel, L.A. (1989a). Nutrient dynamics of tropical forest land before and after conversion to other types of land use. In *Regional Seminar on Tropical Forest Hydrology*, 4-9 September 1989, Kuala Lumpur.
- Bruijnzeel, L.A. (1989b). Nutrient cycling: the hydrological framework. In *Mineral Nutrients in Tropical Forest and Savanna Ecosystems*, ed. J. Proctor, pp. 383-415. Oxford: Blackwell Scientific Publications.
- Bruijnzeel, L.A. (1990). *Hydrology of moist tropical forest and effects of conversion: a state of the art review*. Paris : UNESCO.
- Bruijnzeel, L.A. (1991). Nutrient input-output budgets of tropical forest ecosystems: a review. *Journal of Tropical Forest Ecology*, 7: 1-24.
- Bruijnzeel, L.A. (1992). Managing tropical forest watersheds for production: where contradictory theory and practice co-exist. In *Wise Management of Tropical Forests*, Proceedings of the Oxford Conference on Tropical Forests 1992, eds. F.R. Miller & K.L. Adam. pp. 37-75. Oxford : Oxford Forestry Institute (University of Oxford).
- Bruijnzeel, L.A. (1996). Predicting the hydrological impacts of land cover transformation in the humid tropics: the need for integrated research. In *Amazonian deforestation and climate*, eds. J.H.C. Gash, C.A. Nobre, J.M. Roberts, & R.L. Victoria, pp. 15-55. Chichester: Wiley.
- Bruijnzeel, L.A. (2001). Forest hydrology. In *The Forests Handbook*, ed. J. Evans, pp301-343, Oxford: Blackwell.
- Cailleux, A. (1959). *Etudes sur l'érosion et la sédimentation en Guyane*. Mem. Serv. Carte Geol. Fr., pp 49-73.
- Chappell, N.A. & Terman, J.L. (1992). Flow-path dimensionality and hydrologic modelling. *Hydrological Processes*, 6: 327-345.
- Chappell, N.A., Franks, S.W. & Larenus, J. (1998). Multi-scale permeability estimation for a tropical catchment. *Hydrological Processes*, 12: 1507-1523.
- Chappell, N.A., McKenna, P., Bidin, K., Douglas, I. & Walsh, R.P.D. (1999a). Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. *Philosophical Transactions of the Royal Society of London Series B.*, 354: 1831-1846.
- Chappell, N.A., Terman, J.L. & Bidin, K. (1999b). Correlation of physicochemical properties and sub-erosional landforms with aggregate stability variations in a tropical Ultisol disturbed by forestry operations. *Soil and Tillage Research*, 50: 55-71
- Chappell, N.A., Bidin, K. & Tych, W. (2001). Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest. *Plant Ecology*, 153: 215-229.

- Chappell, N.A., Douglas, I., Hanapi, J.M. & Tych, W. (in submission). Source of suspended-sediment within a tropical catchment recovering from selective logging. *Hydrological Processes*, in submission.
- Collison, A.J.C. & Anderson, M.G. (1996). Using a combined slope hydrology stability model to identify suitable conditions for landslide prevention by vegetation in the humid tropics. *Earth Surface Processes and Landforms*, 21: 737-747.
- Conway, S. (1982). *Logging Practices*. San Francisco : Miller Freeman Publications.
- Croke, J., Hairine, P. & Fogarty, P. 1999. Runoff generation and re-distribution in logged eucalyptus forests, south-eastern Australia. *Journal of Hydrology*, 216: 56-77.
- Dabin, B. (1956). *Note sur le fonctionnement des parcelles expérimentales de l'érosion à la station d'Apiopodioume (Cote d'Ivoire)*. Dakar, Decret Permanent Bureau Sols AOF. Mimeographed, pp16.
- Davies, S.J. (1998). Photosynthesis of nine pioneer *Macaranga* species from Borneo in relation to life history. *Ecology*, 79: 2292-2308.
- Dietrich, W.E. & Dunne, T. (1978). Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie, Supplements*, 29: 191-206.
- Dixon, J.C. (1986). Solute movement on hillslopes in the alpine environment of the Colorado Front Range. In *Hillslope Processes*, ed. A.D. Abrahams, pp. 139-159, Boston : Allen and Unwin.
- Douglas, I. (1996). The impact of land-use changes, especially logging, shifting cultivation, mining and urbanisation on sediment yields in humid tropical Southeast Asia: a review with special reference to Borneo. In *Erosion and Sediment Yield: Global and Regional Perspectives*. pp. 463-471, IAHS publication 236, Paris : IAHS.
- Douglas, I., Greer, T., Sinun, W., Anderton S., Bidin, K., Spilsbury, M., Jadda, S., and Azman, S. (1995). Geomorphology and rainforest logging practices. In *Geomorphology and Land Management in a Changing Environment*, eds. D.F.M. McGregor & D.A. Thompson. Chichester : Wiley.
- Douglas, I., Spencer, T., Greer, T., Bidin, K., Sinun, W. & Wong, W.M. (1992). The impact of selective commercial logging on stream hydrology, chemistry and sediment loads in the Ulu Segama rain forest, Sabah. *Philosophical Transactions of the Royal Society of London Series B*, 335, 397-406.
- Douglas, I. & Bidin, K. (1994). *Effectiveness of buffer strips in reducing the impact of logging on streamflow and stream sedimentation (January 1991-January 1994)*. R4603 Final Report, London : Overseas Development Administration.
- Douglas, I. Bidin, K., Balamurgan, G., Chappell, N.A., R.P.D. Walsh, Greer, T. & Sinun, W. (1999). Role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. *Philosophical Transactions of the Royal Society of London Series* ., 354, 1749-1761.
- Eschenbach, C., Glauner, R., Kleine, M. & Kappen, L. (1998). Photosynthesis rates of selected tree species in lowland dipterocarp rainforest in Sabah, Malaysia. *Trees-Structure and Function*, 12: 356-365.
- Eshleman, K.N. (2000). A linear model of the effects of disturbance on dissolved nitrogen leakage from forested watersheds. *Water Resources Research*, 36: 3325-3335.
- George, R.J. (1992). Hydraulic-properties of groundwater systems in the saprolite and sediments of The Wheat-Belt, Western Australia. *Journal of Hydrology*, 130: 251-278.
- Gilmour, D.A. (1977). Effect of rainforest logging and clearing on water yield and quality in a high rainfall zone of North-east Queensland. In *Symposium on The Hydrology of Northern Australia, Brisbane*. pp. 156-160. Old National Conference Publication No. 7715, Institute of Engineers (Australia).
- Greer, T., Sinun, W., Douglas, I. & Bidin, K. (1996). Long term natural forest management and land-use change in a developing tropical catchment, Sabah, Malaysia. In *Erosion and Sediment Yield: Global and Regional Perspectives*. pp. 453-461, IAHS publication No. 236. Paris : IAHS.
- Gregory, K.J. and Walling, D.E. (1973). *Drainage basin form and process*. London : Arnold.
- Hafkenscheid, R. (2000). *Hydrology and biogeochemistry of tropical montane rain forests of contrasting stature in the Blue Mountains, Jamaica*. Unpublished PhD thesis. Amsterdam : Free University.
- Hardjowitjro, H. (1981). Soil erosion as a result of traditional cultivation in Java Island. In *Proc. South-east Asian Regional Symposium on Problems of Soil Erosion and Sedimentation*, eds. T. Tingsanchali & H. Eggers, pp 173-179. Bangkok : Asian Institute of Technology.
- Hudson, J.A., Crane, S.B. & Blackie, J.R. (1997). The Plynlimon water balance 1969-1995: the impact of forest and moorland vegetation on evaporation and streamflow in upland catchments. *Hydrology and Earth System Sciences*, 1: 409-428.
- Iremonger, S., Ravilious, C. & Quinton, T. (1997). A statistical analysis of global forest conservation. In *A global overview of forest conservation*, eds. S. Iremonger, C. Ravilious & T. Quinton. Cambridge : CIFOR / WCMC.
- Jakeman, A.J., Chen, T.-H., Post, D.A., Hornberger, G.M., Littlewood, I.G. & Whitehead, P.G. (1993). Assessing uncertainties in hydrological response to climate at large scale. In *Macro-scale Modelling of the Hydrosphere*, ed. W.B. Wilkinson, pp. 37-47. IAHS publication 214. Paris : IAHS.
- Jakeman, A.J. & Hornberger, G.M. (1993). How much complexity is warranted in a rainfall-runoff model ? *Water Resources Research*, 29: 2637-2649.
- Jetten, V.G. 1994. Modelling the effects of logging on the water balance of a tropical rainforest: A study in Guyana. Unpublished PhD thesis. Utrecht : University of Utrecht.
- Jetten, V.G., Riezebos, H. Th., Hoefsloot, F. & van Rossum, J. 1993. Spatial variability of infiltration and related properties of tropical soils. *Earth Surface Processes and Landforms*, 18: 477-488.
- Jones, J.A.A. (1990). Piping effects in humid lands. In *Groundwater Geomorphology*, eds. C.G. Higgins & D.R. Coates, pp. 111-138, Special Paper 252. Boulder : Geological Society of America.
- Kobayashi, S., Turnbull, J.W. & Cossalter, C. 2001. Rehabilitation of degraded tropical forest ecosystems project. In *Rehabilitation of degraded tropical forest ecosystems*, eds. S. Kobayashi, J.W. Turnbull, T. Toma, T. Mori, & N.M.N.A. Majid, pp. 1-16, Workshop proceedings, 2-4 November 1999, Bogor, Indonesia. Bogor : Center for International Forestry Research.
- Lai, F.S. (1992). *Sediment and solute yields from logged, steep upland catchments in Peninsular Malaysia*, Unpublished PhD thesis. Manchester : University of Manchester.
- Lai, F.S. Geoffery, J.G. Hamdan, A.G. & M. Jafri, H. (1999). Post-logging sediment yield of the Sungai Lawing Basin, Selango, Malaysia. In *Water: Forestry and Landuse Perspectives*, Proceedings of the CFFPR conference, Forestry Research Institute of Malaysia (FRIM), 31 March to 1 April 1999. Kuala Lumpur : FRIM.
- Larsen, M.C. & Torres-Sanchez, A.J. (1998). The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico. *Geomorphology*, 24: 309-331.
- Larsen, M.C., Torres-Sanchez, A.J. & Concepcion, I.M. (1997). Watershed sensitivity to land use and lithology: a comparison of fluvial sediment yield in four small montane tropical catchments, Puerto Rico. *EOS Transactions American Geophysical Union*, 78:.
- MacDonald L.H, Sampson R.W, Anderson D.M. 2001 Runoff and road erosion at the plot and road segment scales, St John, US Virgin Islands. *Earth Surface Processes and Landforms*, 26: 251-272.
- Malmer, A. & Grip, H. (1990). Soil disturbance and loss of infiltrability caused by mechanised and manual extraction of tropical rainforest in Sabah, Malaysia, *Forest Ecology and Management*, 38: 1-12.
- Malmer, A. & Grip, H. (1994). Converting tropical rain-forest to forest plantation in Sabah, Malaysia. 2. Effects on nutrient dynamics and net losses in streamwater. *Hydrological Processes*, 8: 195-209.
- Martin-Smith K. 1998 Biodiversity patterns of tropical freshwater fish following selective timber extraction: a case study from Sabah, Malaysia. *Italian Journal of Zoology (Suppl. S)*, 65: 363-368.
- Middleton, G.V. (2000). *Data analysis in the earth sciences using MATLAB*. pp260. Upper Saddle River : Prentice-Hall.
- Milliman, J.D., Farnsworth, K.L. & Albertin, C.S. (1999). Flux and fate of fluvial sediment sleaving large islands in the East Indies. *Journal of Sea Research*, 41: 97-107.
- Nash, J.E. & Sutcliffe, J.V. (1970). River flow forecasting through conceptual models, 1: A discussion of principles. *Journal of Hydrology*, 10: 282-290.
- Nykvist, N. (1994). Removal of plant nutrient in logs when clear-felling tropical rainforests - a literature review. In *Proc. Symposium on Harvesting and Silviculture for Sustainable Forestry in the Tropics*, eds. Wan Razali, W.M., Shamsuddin I., S. Appanah & M. Farid, A.R., pp. 192-196, Kuala Lumpur : Forest Research Institute of Malaysia.

- Oyebande, L. (1988). Effects of tropical forest on water yield. In *Forest, Climate and Hydrology: Regional Impacts*, eds. E.R.C. Reynolds & F.B. Reynolds, pp 16-50, Japan : The United Nations University.
- Pickup, H., Higgins, R.J. & Warner, R.H. (1981). Erosion and sediment yield in Fly River drainage basins. In *Erosion and Sediment Transport in Pacific Rim Steeplands*, eds. T.R.H. Davies & A.J. Pearce, pp. 438-456, IAHS publication No. 132. Paris : IAHS.
- Pinard, M.A., Putz, F.E., Tay, J. & Sullivan, T.E. (1995). Creating timber harvest guidelines for a reduced-impact logging project in Malaysia. *Journal of Forestry*, 93: 41-45.
- Poels, R.L.H. (1987). *Soils, water and nutrients in a forest ecosystem in Suriname*. Unpublished PhD thesis. Wageningen : Agricultural University.
- Polcher, J. (1995). Sensitivity of tropical convection to land surface processes. *Journal of Atmospheric Sciences*, 52: 3143-3161.
- Post, D.A. & Jakeman, A.J. (1996). Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments. *Hydrological Processes*, 10: 877-892.
- Rahman, Y. (1993). Soil of Singapore. In *Physical Adjustments in a Changing Landscape*, eds. A. Gupta & J. Pitts, pp. 144-189. Singapore : Singapore University Press.
- Restom, T.G. & Nepstad, D.C. (2001). Contribution of vines to the evapotranspiration of a secondary forest in eastern Amazonia. *Plant and Soil*, 236: 155-163.
- Roberts, J., Cabral, O.M.R., Fish, G., Molion, L.C.B., Moore, C.J., & Shuttleworth, W.J. (1993). Transpiration from an Amazonian rain-forest calculated from stomatal conductance measurements. *Agricultural and Forest Meteorology*, 65: 175-196.
- Searcy, J.K. (1959). *Flow-duration curves*. Wat. Sup. Pap. 1542-A. Washington D.C. : USGS.
- Searcy, J.K. & Hardison, C.H. (1960). *Double-mass curves*. Water Supply Paper 1541-B. Washington D.C. : USGS
- Sellers P.J., Heiser M.D., Hall F.G., Goetz S.J., Strebel D.E., Verma S.B., Desjardins R.L., Schuepp P.M., MacPherson, J.I. (1995). Effects of spatial variability in topography, vegetation cover and soil moisture on area-averaged surface fluxes: A case study using the FIFE 1989 data. *Journal of Geophysical Research - Atmospheres*, 100(D12): 25607-25629.
- Sheffield AT, Healy TR, McGlone MS. 1995 Infilling rates of steepland catchment estuary, Whangamata, New Zealand. *Journal of Coastal Research*, 11: 1294-1308.
- Singh, R.B. (1998). Land use cover changes, extreme events and ecohydrological responses in the Himalayan region. *Hydrological Processes*, 12: 2043-2055.
- Spaans, E.J.A., Bouma, J., Lansu, A. & Wielemaker, W.G. 1990. Measuring soil hydraulic properties after clearing of tropical rain forest in a Costa Rican soil. *Trop. Agric. (Trinidad)*, 67: 61-65.
- Stevens, P.A., Norris, D.A., Williams, T.G., Hughs, S., Durrant, D.W.H., Anderson, M.A., Weatherley, N.A., Hornung, M. & Woods, C. (1995). Nutrient losses after clearfelling in Beddgerlert Forest - a comparison of the effects of conventional and whole-tree harvest on soil-water chemistry. *Forestry*, 68: 115-131.
- Subba Rao, B.K., Ramola, B.C. & Sharda, V.N. (1985). Hydrologic response of a forested mountain watershed after thinning. *Indian Forester*, 111: 681-690.
- Swank, W.T. (1988). Stream chemistry responses to disturbance. In *Forest Hydrology and Ecology at Coweeta*, eds. W.T. Swank & D.A. Crossley Jr., pp. 339-357, Ecological Studies, Vol. 66. New York : Springer-Verlag.
- Swank, W.T., Swift, L.W. & Douglass, J. (1988). Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In *Forest Hydrology and Ecology at Coweeta*, eds. W.T. Swank & D.A. Crossley Jr., pp. 297-312, Ecological Studies, Vol. 66. New York : Springer-Verlag.
- Swanston, D.N., and Swanson, F.J. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. In *Geomorphology and Engineering*, ed. D.R. Coates, New York: Halsted Press.
- Tundisi, J.G. (1990). Perspectives for ecological modeling of tropical and subtropical reservoirs in South America. *Ecological Modelling*, 52: 7-20.
- van der Plas, M.C. & Bruijnzeel, L.A. (1993). Impact of mechanized selective logging of rainforest on topsoil infiltrability in the Upper Segama areas, Sabah, Malaysia. In *Hydrology of Warm Humid Regions*. pp. 203-211, IAHS publication 216. Paris : IAHS.
- van Dam, O. (2001). *Forest Filled with Gaps: Effects of Gap Size on Water and Nutrient Cycling in Tropical Rain Forest*, Unpublished PhD thesis. Utrecht : Utrecht University.
- van der Hout, P. (1999). *Reduced impact logging in the tropical rainforest of Guyana: Ecological, economic and silvicultural consequences*. Unpublished PhD thesis. Utrecht : Utrecht University.
- Walling, D.E. & Webb, B.W. (1983). Erosion and sediment yield. In *Background to Palaeohydrology*, ed. K.J. Gregory, pp 69-100. Chichester : Wiley.
- Ward, R.C. (1981). River systems and river regimes. In *British Rivers*, ed. J. Lewin, pp. 1-33. London : Allen and Unwin.
- Wheater, H.S., Jakeman, A.J. & Beven, K.J. (1993). Progress and directions in rainfall-runoff modelling. In *Modelling Change in Environmental Systems*, eds. A.J. Jakeman, M.B. Beck & M.J. McAleer, Chichester : Wiley.
- Whitmore, T.C. & Burnham, C.P. (1969). The altitudinal sequence of forests and soils on granite near Kuala Lumpur. *Malayan Nature Journal*, 22: 99-118.
- Young, P.C. (1984). *Recursive estimation and time series analysis*. Berlin : Springer.
- Young, P.C. (1992). Parallel processes in hydrology and water quality: a unified time-series approach. *Journal of the Institute of Water and Environmental Management*, 6: 598-612.
- Young, P.C. 2001. Data-based mechanistic modelling and validation of rainfall-flow processes. In *Model validation: perspectives in hydrological sciences*, eds. M.G. Anderson and P.D. Bates, Chichester: Wiley
- Young, P.C. & Beven, K. (1994). Data-based mechanistic modelling and the rainfall-flow non-linearity. *Environmetrics*, 5: 335-363.
- Young, P.C., Jakeman, A.J. & Post, D.A. (1997). Recent advances in the data-based modelling and analysis of hydrological systems. *Water Science and Technology*, 36: 99-116.
- Young, P.C. (1998). Data-based mechanistic modelling of environmental, ecological, economic and engineering systems. *Environmental Modelling and Software*, 13: 105-122
- Young, P.C., Pedregal, D.J. & Tych, W. (1999). Dynamic harmonic regression. *Journal of Forecasting*, 18: 369-394.
- Yusop, Z. (1989). Effects of selective logging methods on dissolved nutrient exports in Berembun Watershed, Peninsular Malaysia. In *Regional Seminar on Tropical Forest Hydrology*, 4-9 September 1989, Kuala Lumpur.
- Yusop, Z. (1996). *Nutrient cycling in secondary rainforest catchments of Peninsular Malaysia*. Unpublished PhD thesis, Manchester : University of Manchester.

