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THE ROYAL SOCIETY

Hydrological investigations of forest disturbance and land cover impacts in South-East Asia: a review

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Investigations of land management impacts on hydrology are well developed in South-East Asia, having been greatly extended by national organizations in the last two decades. Regional collaborative efforts, such as the ASEAN–US watershed programme, have helped develop skills and long-running monitoring programmes. Work in different countries is significant for particular aspects: the powerful effects of both cyclones and landsliding in Taiwan, the significance of lahars in Java, of small-scale agriculture in Thailand and plantation establishment in Malaysia. Different aid programmes have contributed specialist knowledge such as British work on reservoir sedimentation, Dutch, Swedish and British work on softwood plantations and US work in hill-tribe agriculture. Much has been achieved through individual university research projects, including PhD and MSc theses. The net result is that for most countries there is now good information on changes in the rainfall–run-off relationship due to forest disturbance or conversion, some information on the impacts on sediment delivery and erosion of hillslopes, but relatively little about the dynamics and magnitude of nutrient losses. Improvements have been made in the ability to model the consequences of forest conversion and of selective logging and exciting prospects exist for the development of better predictions of transfer of water from the hillslopes to the stream channels using techniques such as multilevel modelling. Understanding of the processes involved has advanced through the detailed monitoring made possible at permanent field stations such as that at Danum Valley, Sabah.

Keywords: erosion; sediment yield; forestry; South-East Asia; roads; landslides

1. INTRODUCTION

Through the 1970s and 1980s, South-East Asia was the leading source of timber for the international tropical hardwood trade. This followed a tradition of forest harvesting and management for timber production traceable back 100 years to the colonial forest services of the Indian Empire, of the Dutch East Indies and French Indo-China. Since 1960, the forest services and the timber companies have become locally based and the majority of the accessible lowland forests have already been harvested by selective logging at least once, or have been cleared for other land uses. The large South-East Asian timber companies are now seeking concessions in the countries of the South-West Pacific and South America. This lead in commercial forest exploitation for international trade has put South-East Asian forests in the forefront of international scrutiny, yet in many ways, commercial exploitation offers the best opportunities for improved forest management. Change is easier to introduce into a large concession managed by a single agency than into a forest occupied by a variety of social groups using forest resources in conflicting ways and under pressure to supply fuel wood and timber to expanding local towns and cities.

South-East Asia differs from the main tropical rainforest areas of the Amazon and Congo in that they occupy sedimentary basins on ancient Gondwana shield rocks, whereas South-East Asia has great geological diversity, with the island arcs of active tectonism and volcanicity. Central America offers some parallels with the latter, but in many places, South-East Asian population densities are much higher than in the Americas. The diverse conditions of South-East Asia are an ideal testing ground for hypotheses and guidelines developed from detailed investigations in specific sites. They also provide cautionary lessons on the degree to which solutions that have worked in one tropical rainforest can be transported to another. This paper therefore sets out to examine what is known about erosion rates and processes in different types of natural terrain in South-East Asia and then to review the effects of forest disturbance, especially by selective logging and shifting cultivation. The aim is to establish the range of magnitudes of increases in soil loss and sediment yields, during and after disturbance, and examine how far hydrological and geomorphic process research has been able to contribute to improved guidelines for forest management.

Water resources management, provision of urban water supplies, irrigation development and exploitation of hydroelectric potential have long been drivers of hydrological investigations in the countries of South-East Asia. Both agriculture and forestry departments have had interests in the risks of soil erosion and land degradation affecting crop and timber production. Scientific work on hydrology and erosion has tended to follow these practical

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interests, but since 1960, a growth in local universities and scientific infrastructure, coupled with increased activity by international organizations and bilateral partnerships between local and overseas institutions has led to an upsurge in broader investigations. Much of the interest has been in the behaviour of the natural environment, the water and nutrient balance of the natural forest. However, that environment is extremely complex, both geologically and climatically, and no account of hydrological findings would be complete without an analysis of the region's geomorphological diversity.

2. DATA ON THE NATURAL ENVIRONMENT

Analysis of the effects of changes in land use and management practices and land cover requires baseline data on natural processes in undisturbed forests to act as a reference against which the effects of human activity may be judged. Care has to be taken to ensure that the natural and disturbed areas compared are as similar as possible. Across South-East Asia there is probably greater variation in rates of run-off and rates of soil erosion under natural conditions than there is at one site before and after disturbance. Due account must be taken of the geological and climatic contrasts within South-East Asia.

(a) *Variability due to climate and geology*

Major controls on regional denudation rates (or sediment yields) include climate and geology, with human activity becoming increasingly important in the 20th century. While much has been written about how natural denudation rates appear to vary with climate (Fournier 1960; Douglas 1967; Strakhov 1967; Walling & Webb 1983) the geological influences have seldom been analysed in a regional context. Geology is expressed through the rocks and soil properties of the catchment area and the tectonic style of the terrain over which the catchment is developed. The highest sediment yields occur in tectonically active areas, where earth tremors trigger frequent mass movements which supply large volumes of sediment to rivers. The lowest sediment yields are on old land surfaces of low relief and deep weathering profiles. The contrast quantitatively is the difference between yields of the order of 10 000 t km^{-2} yr^{-1} in mountains of New Guinea, Taiwan and the South Island of New Zealand (Pickup *et al*. 1981; Shimen Reservoir Authority 1975; Griffiths 1979) and yields of around 10 t km^{-2} yr^{-1} in parts of eastern Amazonia and Africa (Milliman & Meade 1983). These differences emerge in tropical rainforest climates where small mountainous rivers discharge great volumes of sediment per square kilometre of catchment area but are largely ignored in global sediment budget calculations (Milliman & Syvitski 1992). For South-East Asia, deductive arguments, based on the scattered data and extrapolations from similar environments elsewhere, suggest that sediment yields of the order of 10 000 t km^{-2} yr^{-1} occur in the most tectonically active parts of the island arcs, with around 1000 t km^{-2} yr^{-1} on the weak Tertiary mud rocks of eastern Borneo and 50–100 t km^{-2} yr^{-1} in the deeply weathered Mesozoic granites of the Thai-peninsular Malaysia-Bangka intrusive complex (Douglas 1992; Curtis & Douglas 1993). South-East Asian catchment studies now provide sufficient evidence to test this hypothesis and to examine the impacts of different forms of disturbance.

The effects of tectonics and vulcanicity are dramatic and rapid in occurrence, but may last for long after the initial event. Most rivers in Indonesia, and many in the Philippines, originate in volcanic regions. Volcanic eruptions cause enormous flows of ash and lava into these rivers. This debris is easily eroded and often turns into lahars, masses of water-saturated volcanic ash, after rain. Lahars erode the sediment of river-beds and banks and achieve considerable size and enormous energy, causing considerable damage. Mabinit Channel, 5 km long, 15–70 m wide, and 2–22 m deep, was formed by lahars on the south-eastern slope of Mayon Volcano, on the Philippine island of Luzon, during its 1984 eruption. Following a typhoon in 1985, a lahar swept downvalley and drastically modified the channel. Sediment-budget calculations have corroborated inferences from other volcanoes that lahars can grow significantly in volume by eroding their channels (Rodolfo 1989). Rain-induced lahars, reworking volcanic debris and mud, on Mayon Volcano since its last eruption in 1984 have been triggered by rainstorms of at least 40 mm magnitude lasting at least 1.4 h, within an overall intensity of 11 mm h^{-1} or more, and including at least one 10-min period with a 60 mm h^{-1} intensity (Rodolfo & Arguden 1991).

Control of excessive volcanic sediment flow has been achieved to a great extent using checkdams built in steep-gradient river-beds, but the optimum requirements of these are still indeterminate. To localize the spread of volcanic material, lahar pockets are built across the streams. The design of lahar pockets follows experience gained in the past. River courses will be improved by bed excavation, bank protection works and groynes (Legowo 1981).

(b) *Landsliding in undisturbed forest areas*

Landslides are a natural phenomenon on steep forested slopes throughout South-East Asia but slopes underlain by certain rock types are more susceptible to slipping than others. Naturally occurring landslides may be more common than casual observation suggests. Some 120 major landslide scars were recorded by Day (1980) in the Gunung Mulu National Park, Sarawak, Malaysia, some multiple scars having a combined length of 250 m and width of 200 m. In the vicinity of Gunung Api, three slide scars covered 60 000m^2 and another eight separate scars covered 70% of a slope area. Day (1980) considered heavy storms to have been the main trigger for a number of landslides observed in the Gunung Mulu National Park in Sarawak. Increases in pore water pressure during heavy storms or when drainage is impeded cause failure.

Most of the slides observed in the Gunung Mulu National Park were situated on the lower slope sections although landslides are clearly associated with steep slopes. Out of 21 landslides examined at Gunung Mulu, all were located on slopes in excess of 40° and 18 on slopes in excess of 50° (Day 1980). In nearby Brunei, at Ulu Temburong, landsliding contributes about 16.5% of the annual erosion rate (Dykes 1995). The weathered and fractured slaty shales of the Mulu Formation are clearly prone to slipping, with most of the slides occurring on slopes parallel to the dip of the rocks. In Peninsular

Malaysia, landslides occur on slopes underlain by granitic rocks, as on the slopes of the Main Range of Peninsular Malaysia during the exceptional rainfalls of late December 1926 and January 1971.

Major storms of 20–23 November 1988, which gave a three-day total rainfall of 885 mm triggered large-scale landsliding in the Nakhon Si Thammarat Range of Phipun District in southern Thailand. The change in land use in the Phipun district from rainforest to rubber plantation may have contributed to the landsliding. In a catchment of 92 km^2 the debris avalanche and debris transported *ca.* 107 t km^{-2}. The minimum annual erosion rate in this area with this sort of landsliding every 150–300 years would be 356–712 t km^{-2} yr^{-1} (Harper 1995). Further landsliding occurred at least twice in 1997 in southern Thailand, in association with heavy rains in August and November.

Similar to lahars, landslides supply sediment to slope foot areas, channel heads and stream channels, where it may partially block, or even divert, the stream. Much of this added sediment may not be moved further until subsequent large rain events erode material and carry it further downstream.

(c) *Baseline reference information*

Many observations and measurements have clearly indicated that soil losses from rainforested slopes are seldom excessive (e.g. Chatterjea 1989; Sinun *et al*. 1992; Walsh 1993). Patches of bare ground are uncommon and eroding rills and gullies rare. Close examination of the forest floor will, however, often locate ephemeral wash lines along which some sediment must be transported, eventually reaching stream courses. Contrary to common belief, litter does not often thickly blanket the forest floor, being typically only 1–3 cm deep and sometimes patchy (Leigh 1982; Besler 1987), and a direct relationship between the nature of the litter cover and volumes of surface wash and suspended sediment has been demonstrated in experimental studies (Peh 1976, 1980; Leigh 1982). In some rainforested areas in Malaysia, run-off and detached sediment may be washed into streams through pipes in the upper layers of the soil (Baillie 1974; Brooks *et al*. 1993).

The main source of sediment in rainforest streams and rivers is probably derived from eroding watercourse banks. Not unsurprisingly, it would appear that significant proportions of total river sediment loads are transported during severe storm events, which also detach and transport relatively high proportions of soil lost from hillslopes (Douglas *et al*. 1993). For example, 57% of the sediment transported from a natural forest plot in Sarawak over a 12 month period was removed in a single month (Hatch 1981).

Care should therefore be taken in interpreting and using the limited amount of quantitative data that is available because the rainforest environment is far from uniform. Rates of soil erosion can be expected to be higher in areas of steep terrain, although slope angle may not be as important as previously thought in forest where there is sufficient litter and exposed roots to impede any overland flow and where 90% or more of the water reaching the ground surface infiltrates (Douglas *et al*. 1992*a*; Brooks *et al*. 1993). Also some rock types are more susceptible to erosion than others. It is also possible that rates of erosion vary under different rainforest types in relation to differences in rates of interception and the nature of the ground cover. In addition, it would appear likely that many reported values for rates of sediment transport on slopes and in streams may have been underestimated because peak storm events were not recorded (Douglas *et al*. 1993). The available information indicates that rates of soil erosion and transportation are generally relatively low in rainforested areas in Malaysia. This can be attributed to a number of factors:

(i) the protective effect of the rainforest trees and understorey, especially in breaking the fall of raindrops and trapping much of the small amount of soil moved downslope against exposed roots and buttresses; the interception of between 21.8 and 36.0% of annual rainfall (Low 1971; Manokaran 1977) and high transpiration by the vegetation reduce the water held in the soil so that saturated conditions only develop over restricted stream head areas and seldom extend further upslope, except in the largest storms occurring once or twice a year;
(ii) the protective nature of the litter cover;
(iii) the general absence of areas of bare ground;
(iv) the relatively high infiltration capacities and permeabilities of undisturbed forest soils, which reduce overland flow quantities and frequencies;
(v) the vegetated nature of stream and river-banks.

Nutrient cycling studies in South-East Asia have considered imports in rainfall and exports in stream-flow to be relatively small in comparison with the total nutrient turnover in undisturbed forests (Kenworthy 1971; Bruijnzeel 1995; Zulkifli 1996). Depending on catchment lithology, losses of silicate occur due to the effective rock weathering environment, but catchments appear to accumulate P and Ca.

(d) *Issues of long-term monitoring*

Across South-East Asia and adjoining countries much information has been collected on the effects of land use practices on soil erosion and river sediment yields. Many national agencies regularly report rainfall, evaporation, run-off and sediment yield data for stations on major rivers and their tributaries (for example in the water yearbooks of Thailand and the Philippines and of the Mekong River Commission). Representative basin programmes have been established in several countries, the Malaysian Drainage and Irrigation Department having developed a programme in the 1960s (Tan 1966) which included the Sungai Lui basin studied by Low (1971), Low & Goh (1972) and Lai (1992). Despite much good data collection on rainfall and run-off, rain-gauge networks are often inadequate for detailed hydrological work, with few stations on catchment divides or in the hills and many catchments only having a rainfall recorder close to the river-gauging station at the catchment's lowest point. Records of water quality and sediment transport are generally incomplete or are not based on detailed event-based sampling. Often water quality data are collected as parts of different projects, or by separate agencies. Few programmes actually provide data for areas of a single land use, such as a segment of natural forest.

Only two water balance studies in South-East Asian humid tropical forest catchments running for over ten years, at Sungai Bedup, Sarawak, Malaysia (Takenouchi 1982) and at Kog-Ma in Thailand (Chunkao *et al*. 1981), are listed by Koichiro (1997). Nevertheless, the national forest research centres of the different countries have promoted a wide range of research studies, often supported by additional work from other agencies, both within and outside the countries concerned. Good examples include the many catchment studies in Thailand and the Bukit Berembun and Bukit Tarek studies by the Malaysian Forest Research Institute. Such investigations have been encouraged by the ASEAN–US Watershed Management Programme which has provided training and manuals to standardize and improve monitoring techniques and management planning (Saplaco 1995). However, in dealing with specific problems, care has to be taken to ensure methods or plans are appropriate for the environment concerned.

(e) *Magnitude of natural erosion processes in extreme events*

In addition to the impacts on landsliding described above, extreme rainfalls dominate erosion on the hillsides and the pattern of sediment discharge by rivers. Plot studies in Thailand (Sheng *et al*. 1981; Sheng 1990) showed that in 1979, 88% of soil loss from a control plot was caused by six storms. In three days in 1981, 3300 $\mathrm{t\,km^{-2}\,yr^{-1}}$ were lost from the control plot during the storm of 2–4 September (Kraayenhagen *et al*. 1981). Almost 25% (43 $\mathrm{t\,ha^{-1}}$) of the 174 $\mathrm{t\,ha^{-1}}$ of soil lost during rain events in 1990 from a traditional hillslope farmed plot at the foot of Mount Makiling in the Philippines was lost on 24 August 1990 when 218 mm fell in one day (Paningbatan *et al*. 1995).

A four-year study of rainfall, run-off and sediment yield in the Philippines demonstrated that tropical cyclones, which on average occur twice a year in this region, are extreme events in terms of rainfall, discharge and the amount of sediment eroded and transported (White 1990). Particular attention has to be paid to events like cyclones in estimating sediment yields in the cyclone-affected parts of South-East Asia. In years where no cyclones occur, sediment yields may often be much lower than in other years. Sediment sampling during cyclonic rains, which tend to be of long duration, high intensity and over large areas, is difficult, especially if automatic samplers are not available, or if the samplers are inaccessible when access routes are flooded.

The storm of 19 January 1996 in the Sungai Segama river in south-eastern Sabah, Borneo, produced 178 mm in 11 h and caused the river to discharge 29% of the total suspended sediment load for four years in just 24 h (Douglas 1998*a*; Douglas *et al*. 1999).

3. HYDROLOGICAL AND EROSION DATA AND RESEARCH IN SOUTH-EAST ASIA

(a) *Importance of work by national forest and water resource departments and local research organizations*

Basic hydrological data collection in South-East Asia is usually the responsibility of drainage and irrigation organizations, although typically river-flow data may also be collected by agencies responsible for hydroelectricity, urban water supplies, forest management and soil conservation and land development. In many countries there is excellent collaboration between agencies and reliable water yearbooks containing stream gauging information are published (e.g. Department of Drainage and Irrigation, Sarawak, Malaysia 1991; National Energy Authority of Thailand 1966; Mekong River Commission 1996). Such documents may also contain data on rainfall, evaporation pan measurements and, sometimes, water quality and suspended sediment concentrations.

In addition to the routine data collection, research is conducted by a variety of national organizations, particularly in terms of soil erosion and small catchment hydrology. Some of these investigations are stimulated by international funding, such as the support from Scandinavian countries for erosion and sedimentation studies by the Mekong River Commission in which field measurements are subcontracted to national agencies in the individual countries. Others form part of the long-term research strategies of the countries concerned. Outstanding among these are the forest hydrology studies of the Royal Thai Forest Department and the Forest Research Institute of Malaysia (FRIM).

Thailand has many plot and catchment experiments set up under the watershed management programmes of by the Royal Forest Department and the Division of Land Development of the Ministry of Agriculture. Catchment studies, conducted for periods of up to 15 years, have suggested that sediment yields from undisturbed forests range from 6 $\mathrm{t\,km^{-2}\,yr^{-1}}$ in mixed deciduous forest to 35 $\mathrm{t\,km^{-2}\,yr^{-1}}$ in hill evergreen forest (table 1). A typical study is the Mae Klong Watershed Research Station in Kanchanburi Province, 250 km west of Bangkok where five small catchments, each with a different land use are operated. Land cover represented are upland agriculture and rural housing; shifting cultivation; grazing; undisturbed forest; and lowland agriculture and housing (Suksawang & Tangtham 1997).

In Malaysia, FRIM has been involved in three major catchment studies: Sungai Tekam in Pahang, Bukit Berembun in Negeri Sembilan and Bukit Tarekh in Selangor. Land clearance for agriculture at Sungai Tekam led to increases in water yield of 1169 mm and 437 mm over three years in two stages of forest removal (Abdul Rahim 1988). Both total annual water yield and storm run-off increased (table 2). At Bukit Berembun, the extraction of 40% of the commercial tree stock using crawler tractors and winch lorries led to the stream-flow increasing by 70%. However, under a rigorously supervised harvesting procedure, with only 35% of the stock removed and control of roads and tracks as well as a riparian buffer strip, the stream-flow only increased by 40% (Abdul Rahim & Zulkifli 1994). Bukit Tarekh has provided fundamental data on nutrient cycling, including the role of sediment in the removal of nutrients from a forest which had been selectively logged about 30 years before detailed investigations began (Zulkifli 1996). Here suspended sediment, bedload and floating debris account for 18.7% of the export of Mg and 14.5% of that of Ca, but only 8.8% of the P, 6.2% of the N, 1.7% of the K and 0.5% of the Na.

Table 1. *Sediment yields from catchment studies in Thailand*

(Data supplied by Wanchai Viranun, Faculty of Forestry, Kasetsart University, Thailand.)

catchment	area (km^2)	land cover type	suspended sediment yield ($t\,km^{-2}\,yr^{-1}$)
Huai Bo Thong	0.29	mixed deciduous forest	6–27
Mae Thaang	0.11	disturbed dry dipterocarp forest	410–685
Lam Thakhong	1.51	moist evergreen forest	20
Kogma	0.65	hill evergreen forest	35

Table 2. *Effects of forest conversion at the Sungai Tekam experimental catchment*

(Source: after Zulkifli 1996; Balamurugan 1997.)

parameters	phase 1: clearfelling	phase 2: crop establishment
water yield	annual water yield increases by 85% to 470%	water yield gain declined but still higher than from forest condition
storm flow	peak flow up 185%; time to peak reduced by 67%	peakflow decreases but remains higher than under forest condition; time to peak increased by 2 h
infiltration	decreased by 33% to 88%	increased to a level higher than under forest condition
soil erosion	increased by five to seven times	reduced almost to level under forest
sediment yield	increased four times	reduced almost to level under forest
water quality	increased turbidity, specific conductance, Fe and K	returns almost to level under forest
nutrient losses	loss of Ca and Mg increased by 26 and 37%, respectively	persisted for a few years

The recognition at the Federal level of the importance of the Danum Valley Field Centre and the Conservation Area has extended the significance of the collaboration between the Malaysian institutions involved in the Danum Valley Management Field Centre and their research programmes in biology and hydrology. Ten years of hydrological investigations have now produced results which can be compared with those of other field sites (Chappell *et al.*, this issue; Douglas *et al.* 1992*a*,*b*, this issue; Sinun *et al.* 1992)

In the Philippines, detailed water yearbooks have provided high-quality hydrological data since the 1950s. FRIM has carried out an important project on the hydrology of mossy forests above 2300 m elevation (Penafiel 1993).

(b) *Standard forest plot studies*

Many plot studies of land cover effects have been undertaken by forestry and agricultural organizations in South-East Asia. The Royal Thai Forest Department has about 15 research sites across the country where watershed management research involving plot studies has been undertaken. Summaries of the important research at these sites have been compiled by staff and graduate students of the Faculty of Forestry, Kasetsart University. Typical of the intensity of such investigations is the study of forty-five 4 m × 20 m plots (giving three replicates of each of 15 different land uses) in an integrated development project at Pha Wiang Watershed, Khon Kaen Province, Thailand (Vannaprasert & Thongmee 1996). In the five years from 1988 to 1992, run-off and soil loss from cash crop, agroforestry and bare soil treatments were high in the first two years, subsequently decreased, but remained greater than that from a forest plantation treatment.

Several erosion plot studies by agriculture departments provide further data on erosion rates on bare soil and the effect of land cover conversion. A set of important advances has been made under the Australian Centre for International Agricultural Research programme. The management of soil erosion for sustained crop production has applied a common methodology to sites in Malaysia, the Philippines, Thailand and Australia (Ciesiolka *et al.* 1995). By using data-logging equipment to determine the rate of run-off from plots and by measuring sediment concentration through time during run-off events, field data can be used to derive soil erodibility parameters which are a significant improvement on the universal soil loss equation (USLE) for predicting erosion under different agricultural practices in tropical areas.

(c) *Hillslope erosion*

Mechanical logging and road construction in hilly areas have led to much soil compaction and erosion (Burgess 1971; Soane 1986; Kamaruzaman 1988; Malmer & Grip 1990). Mechanized logging on hillslopes in East Kalimantan, Borneo left 30% of the ground bare and damaged (Abdulhadi *et al.* 1981). At Mendolong, Sabah, Borneo, tractor movements during logging degraded 25% of the area involved (Malmer & Grip 1990). The reduction in infiltration caused increases in run-off and soil erosion. Tractor logging caused a loss of 390 $t\,km^{-2}$ over 18.5 months compared with a loss of 51 $t\,km^{-2}$ from

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undisturbed forest in the same period (Malmer & Grip 1990).

Most of the lowland forests of Malaysia have already been harvested on one or more selective logging cycle and much of the lowland forest terrain has been converted to plantation agriculture. New forest resources are thus generally restricted to steeplands and upland areas (Khairi bin Mohd & Abdul Hamid 1987). The impact of logging in the steeplands of the Main Range of Peninsular Malaysia has been discussed by Lai *et al.* (1995). Accordingly, 52% of the steep Sg Batangsi Catchment in Ulu Langat, Selangor were being logged in 1987–1989. The total sediment yield over the period of March 1987 to March 1989 was 5424 t km^{-2}, 94.2% of which were transported in storm events. An average of four bulldozers and four winch lorries were used in the operations. The bulldozers were used to construct roads as well as to haul felled logs to landings, after which they were later transported to a local sawmill by the winch lorries. The mean road and snig track density was 6.1 km km^{-2} (Lai 1992). Wet conditions caused operational difficulties in this steepland environment and timber harvesting stopped during severe rains. Poor road conditions were often reported by foresters overseeing these operations with erosion creating and enlarging rills on the road surface and roadside gullies which fed large quantities of weathered granitic sand and clay downslope and into the stream channels, which had a bed covered with coarse quartz sand.

(d) *Paired catchment studies*

Many of the problems of interpreting existing hydrological records to discover the effects on stream-flow of land cover transformations can be overcome by using the paired catchment method (Hewlett & Fortson 1983; Bruijnzeel & Bremmer 1989). The technique requires a comparison of stream-flow outputs from (at least) two basins of similar size (usually less than 1 km^2), aspect, geology and vegetation. One basin (the control) is left unchanged throughout the observation period, while the other (the experimental or treatment basin) is initially operated without any change for two or more years to calibrate against the control. Thereafter the cover is changed in the treatment basin and the difference in the regression relationship for rainfall against run-off compared with the calibration period is a measure of the impact. Many such experiments have been undertaken (Bosch & Hewlett 1982) but very few have been carried out in the tropics (Bruijnzeel 1986, 1987, 1993).

The impact of forest disturbance on nutrient losses has been reported in three paired catchment studies in Malaysia. Logging impacts were studied at Bukit Berembun in Peninsular Malaysia (Abdul Rahim 1990; Zulkifli *et al.* 1993; Baharuddin 1988) while the impacts of forest clearing and conversion to tree crop plantations were studied at Sipitang, Sabah (Malmer 1990, 1993; Nykvist *et al.* 1994) and at Jengka, Peninsular Malaysia (DID 1989).

At Bukit Berembun, commercial logging resulted in increases in pH, electrical conductivity and concentrations of total dissolved solids, SiO_2, Ca, Fe, K and Na (Zulkifli 1990). At Sipitang, concentrations of major nutrients, especially N, P and K, all increased following disturbance. Following clearfelling of 80% of the catchment at Jengka, electrical conductivity almost doubled, but many individual nutrients did not change dramatically in concentration, except for the K released from the biomass and Fe released from disturbed sediments along new roads and tracks (DID 1989). However, because stream-flow increased, total solute export also became greater.

None of these experiments tackled the problem of non-dissolved nutrient loss in floating plant material or in suspended or bedload sediment. Investigating this issue at Bukit Tarek, Zulkifli (1996) found that nutrient removal in bedload seldom exceeded 1% of solute load, in floating material was usually less than 0.8%, and in suspended particulate matter was usually less than 3% of total solute load. The only exceptions were Ca and Mg losses which were 12 and 16.7%, respectively, of the outputs in the dissolved load.

The question of whether there is a major loss of nutrients in suspended sediment following large increases in erosion due to disturbance remains unanswered. The fragmentary evidence suggests that as suspended sediment loads change much more than solute loads following disturbance, losses of nutrients in non-dissolved form may be more significant than so far measured.

(e) *Problems in sediment yield studies: the sediment delivery issue and the lack of bedload measurements*

Relatively few nested catchment studies have been undertaken in South-East Asia and few investigations have addressed the question of the sediment delivery ratio. Sometimes termed conveyance loss, a decrease in sediment yield as drainage basin size increases is the usual trend. The downstream decrease in sediment yield per unit area may be due to deposition in channels and as overbank deposits, but also reflects the lower yields from tributaries draining areas of less high and steep relief in the lower parts of large catchments. For example, in the Me Nan in Thailand sediment yields decrease from 391 t km^{-2} yr^{-1} in the 12 790 km^2 upper catchment to 128 t km^{-2} yr^{-1} further downstream where the catchment area is 25 491 km^2 (Walling 1983).

A limited study during the 1994 and 1995 wet seasons on the Srepok River in Vietnam (Institute of Meteorology and Hydrology, Hanoi 1998) shows a trend counter to the expected pattern of a smaller sediment yield with increasing catchment size. In June to November 1994, the average monthly yields rose regularly from 1.6 t km^{-2} in the 420 km^2 catchment above Krong Buk to 8.2 t km^{-2} in the 10 500 km^2 catchment above Ban Don. This pattern is typical of areas where catchments with good protection forests in their headwaters give way to highly disturbed areas downstream. Similar conditions occur in the Sungai Kelang catchment above Kuala Lumpur (Douglas 1968), where Balamurugan (1991) observed sediment yields rising from 165 t km^{-2} yr^{-1} in the upper Gombak tributary to 806 t km^{-2} yr^{-1} at the Sulaiman bridge in the city centre.

Bedload studies of two of the affluents of the Tonlé Sap in Cambodia (Carbonnel & Guiscafré 1965) found bedload yields of 0.062 t km^{-2} yr^{-1} in the Stung Sen at Kompong Chamlang and 0.7 t km^{-2} yr^{-1} on the Stung

Kasch Toch at kilometre 142 on the Phnom Penh to Battembang road. The suspended sediment yield of the Stung Sen is $0.61\,t\,km^{-2}\,yr^{-1}$, making the bedload approximately 10% of the total sediment load.

More recent bedload transport studies include investigations in undisturbed and selectively logged rainforests in the Main Range in Peninsular Malaysia (Lai 1993), in the secondary forests at Bukit Tarekh, Peninsular Malaysia (Zulkifli 1996) and careful measurements in Vietnam, on the Sesan and Srepok tributaries of the Mekong, using a Helley–Smith bedload sampler lowered from a boat at different points across the rivers (Institute of Meteorology and Hydrology, Hanoi 1998). In the disturbed small streams studied in the Malaysian Main Range (catchment areas of 4.7–68.1 km), bedloads ranging from 22 to $1264\,t\,km^{-2}\,yr^{-1}$ accounted for between 20 and 70% of the total sediment load, the highest per cent bedload occurring in the smallest, steepest stream which had sufficient transfer capacity to transport all delivered materials. The other streams were considered to have bedload of the order of 20–30% of the total sediment load (Lai 1993). In the stable secondary forests logged 30 years prior to bedload investigations at Bukit Tarekh, the two catchments (areas 0.32 and $0.34\,km^2$) had mean annual bedloads for the four years 1991–1994 of 13.1 and $13.9\,t\,km^{-2}\,yr^{-1}$ (Zulkifli 1996), which are high compared with those reported in Cambodia but less than the lowest value for the Malaysian Main Range study.

The studies on larger streams (2910 and $3139\,km^2$) in Vietnam (Institute of Meteorology and Hydrology, Hanoi 1998) demonstrate that while bedload averages about 20% of the total load, its significance varies from month to month (figure 1). Monthly data for seven months in 1994 and 1995 at two sampling sites on the Sesan revealed that bedload accounted for between 5 and 64% of the total sediment load in individual months. The lowest proportion occurred in the month of highest suspended sediment discharge when the transport capacity of the river was greatest and coarse sand particles normally rolled as bedload were probably thrown into suspension.

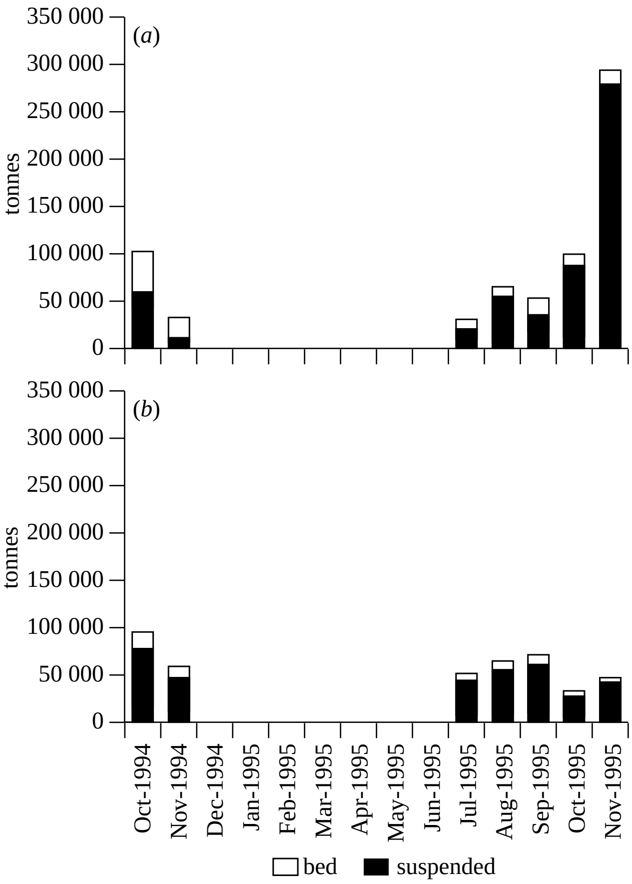

Figure 1. Contrasts between measured suspended sediment loads, based on depth-integrated sampling at five verticals across the river, and bedload, based on sampling with a Helley–Smith bedload sampler at five points across the river, in the Sesan River (*a*) at Kontum (catchment area $2910\,km^2$) and (*b*) at Trung Nhia (catchment area $3139\,km^2$), Vietnam (based on data from the Institute of Meteorology and Hydrology, Hanoi 1998).

(f) *Shifting cultivation in forest areas: a gap in detailed scientific investigations?*

Despite years of writing about the impacts of shifting cultivators on hydrology and soil erosion, few detailed investigations have been made of their true effects. In areas of traditional cultivation where the pressure on land resources is light and fallow periods are long, both field inspection and aerial photograph interpretation reveal little evidence that large quantities of sediment are eroded from newly cleared, burnt fields prepared for hill rice planting. Such observations by the author in Malaysian Borneo are largely confirmed by plot studies conducted by the Sarawak Department of Agriculture for 11 years (Hatch 1981, 1983, 1984; Ng & Teck 1992; Teck 1992) which indicate that under shifting cultivation with long fallows, soil erosion differs little from that under natural forest (table 3).

Elsewhere in South-East Asia, conditions are quite different, there often being too little land for long fallows to occur. From the LaoPDR to Borneo, farmers report decreases in the length of fallows, many using the same fields for three or four years before clearing new land. This continued cultivation accelerates land degradation, but little is known about the precise rates of erosion involved. Analysis of soil erosion damage in different cultivated fields on the steep upland slopes of the Huai-Thung Choa area of northern Thailand indicated annual soil losses of the order of $10\,000\,t\,km^{-2}\,yr^{-1}$, much greater than the $10–20\,t\,km^{-2}\,yr^{-1}$, reported from Sarawak (table 3). Process studies to evaluate USLE parameters on microtest plots at the northern Thailand site during the 1980 monsoon led to prediction of a soil loss of $10\,000–15\,000\,t\,km^{-2}\,yr^{-1}$ from cultivated hill rice plots (Hurni 1982). Other Thai plot studies (Tangtham 1997) report losses of 45 and $80\,t\,km^{-2}\,yr^{-1}$ under shifting cultivation, compared with losses of 30–$100\,t\,km^{-2}\,yr^{-1}$ from natural forests. In the Bayhang watershed near Leyte Mountains National Park, Philippines, mean soil losses of $42\,200\,t\,km^{-2}$ occurred during the first six months of cultivation on recently cleared farms (Siebert 1990).

In an overview of the soil erosion situation in Thailand, Samrit *et al.* (1997) report that some $68\,200\,km^2$ of the country subject to shifting cultivation, rubber, orchard, field crop and agroforestry production experience soil erosion rates of $10–10\,000\,t\,km^{-2}\,yr^{-1}$, with a further

Table 3. *Data on erosion rates under forest and shifting cultivation for Sarawak*

(After Ng & Teck 1992; Teck 1992.)

land use	location	slope (degrees)	period (years)	soil loss mean ($t\,km^{-2}\,yr^{-1}$)	soil loss range ($t\,km^{-2}\,yr^{-1}$)
primary forest	Niah F.R.	25–30	4	19	8–31
	Semongkok	25–30	11	24	7–77
secondary forest					
logged ten years previously	Niah F.R.	25–30	4	23	11–36
with hill padi	Semongkok	25–30	11	10	2–17
two-month-old lallang and scrub	Niah F.R.	33	3	1100	450–1800
hill padi/shifting cultivation					
normal	Kg. Benuk	25–30	1	18	16–20
terraced with cover	Semongkok	20	11	120	21–246
bush fallow	Semongkok	16–26	3	23	6–45
bush fallow	Tebedau	25	2	34	22–46
traditional pepper	Semongkok	25–30	11	8944	5118–13 912

62 600km^2 of steep hill country under shifting cultivation and field crops experiencing extremely severe losses in excess of 10 000$t\,km^{-2}\,yr^{-1}$. Clearly, there is great diversity in soil loss from shifting cultivation, often due to contrasts in lithology, soil and climatic conditions, but also probably reflecting differences in farming practices, and in the methodology of plot studies. The average results from standard plots will not accurately reflect actual losses at the field scale.

(g) *Impacts of forest conversion to agriculture*

Two Malaysian studies of rainforest conversion to oil palm and cocoa plantation at Sungai Tekam in Pahang (DID 1986, 1989) and to forest plantation at Mendolong, Sabah (Malmer & Grip 1993), provide detailed evidence of the hydrological and erosional response to forest removal.

The Sungai Tekam Experimental Basin is in the north of the Jengka Triangle land development area in Pahang. The natural hill dipterocarp rainforest had been logged previously. Calibration began in July 1977 and monitoring continued until the end of 1986. The comprehensive collaborative programme sought to establish the effects of land use changes on the hydrology of the basin, water quality and soil fertility, and to assess the effectiveness of buffer strips and cover crops in soil and water conservation. Two catchments were selected, one of which (catchment C) remained under rainforest cover as the control. The other was divided into two subcatchments with one being converted to cocoa (catchment A) and the other to oil palm (catchment B) (DID 1986).

Predictably, clearfelling and replacing the forest cover with cocoa and oil palm resulted in marked increases in stream sediment loads. In catchment B, clearfelling was followed by an annual sediment load of 414$\,t\,km^{-2}$ in contrast with values of 20, 25 and 39$\,t\,km^{-2}$ for the three preceding years. Substantial increases were also recorded in catchment A, ranging from 10 to 35$\,t\,km^{-2}$ prior to logging but rising to 50 and 125$\,t\,km^{-2}$ following clearfelling. Clearfelling was immediately followed by the planting of cocoa and oil palm in catchments A and B, respectively. By the time the oil palms were two years old, sediment loads had returned to predevelopment levels reflecting the effectiveness of the ground cover crop that was established. In contrast, sediment levels in the catchment planted with cocoa had not returned to near predevelopment levels some three years after planting clearly indicating that the shade trees that were planted did not provide as effective a cover as do ground crops.

At Mendolong, Sabah, five catchments were selected to study the impact of clearfelling and plantation forestry on hydrology and soil properties. One investigation, using two catchments, 3.4 and 18.2 ha in size, examined the impact of mechanized and manual timber extraction on soil disturbance and loss of soil infiltrability (Malmer & Grip 1990). The two catchments lie on the slope of a ridge on the Miocene Maligan sedimentary formation, which is largely made up of sandstones and siltstones with interbedded shales (Malmer 1993). The vegetation of the two catchments was logged over lowland dipterocarp rainforest. Slopes are moderately steep with some steeper segments. Two different soil types are present, one with a relatively high clay content and the other with a relatively high sand content.

Both catchments had previously been selectively harvested in 1981 using crawler tractors and many tracks were still visible in November 1987 when the experiment commenced. The study involved clearfelling both catchments, one following standard commercial practice using crawler tractors and the other using the traditional manual 'kuda-kuda' method whereby logs are hauled on sleds by teams of men along wooden tracks to roadways or rivers (Brown 1955). Measurements indicated that there were considerable increases in the dry bulk density and reductions in the infiltrability of the clay soils where tractors were used to extract timber and that there was practically no difference between the infiltration capacities of the new and six-year-old tractor tracks. In contrast, the soil conditions in the areas where manual extraction was practised differed little from those in the undisturbed forest. Forest clearance led to increased runoff (table 4), particularly in the burnt catchments and that in which tractors were used.

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Table 4. *Increases in run-off (mm) from different catchments at Mendolong, Sabah, subjected to contrasting forestry treatments*

(Source: Malmer 1992.)

catchment	year 1	year 2	year 3	total over three years
W1 + 2	397	522	89	1008
W4	197	170	80	447
W5	460	262	468	1190

4. USING HYDROLOGY AND GEOMORPHOLOGY TO IMPROVE FOREST MANAGEMENT

(a) *Forest hydrology in forest management: incorporation of hydrological criteria into the planning of forestry operations*

Guidelines on forest management include many measures designed to reduce the impacts of logging on run-off and soil loss (Forestry Department, Malaysia 1988).

Increasingly planning of forest operations is using remote sensing and geographical information systems (GIS) to designate coupe areas, taking advantage of the slope and drainage calculation routine in GIS software. Pioneering work has been undertaken by the ASEAN Institute of Forest Management, by Chiangmai University and the Royal Thai Forest Department, by the Sarawak and the Sabah Forest Departments and through collaboration with German foresters (Bossel & Bruenig 1989; Bruenig 1993).

Much emphasis is placed on understanding the relationship between forest degradation and the people living within, or on the margins of, the forest. One such study in Indonesia (Gastellu-Etchegorry & Sinulingga 1988) set out to determine the main relationships between forest degradation and the socio-economic and physical characteristics of a study area south of Banjarnegara (Central Java). Panchromatic (1946; 1:50 000) and colour infrared (1981; 1:30 000) aerial photographs, an official forest map, physical data for soils, topography and erosion, and socio-economic data such as density of farmers and incomes were used to build a GIS on a microcomputer. This GIS permitted easy and quick understanding of the principal local socio-economic relationships and their influence on forest change (Gastellu-Etchegorry & Sinulingga 1988). Many models developed in temperate areas can be linked to GIS to improve watershed assessment and planning in Asia (Dyke 1996).

(b) *Managing roads and tracks in forest areas*

Roads play a major role in altering near-surface conditions in disturbed forests and in the supply of sediment to streams (Bruijnzeel & Critchley 1994; Ziegler & Giambelluca 1997). In the Mae Taeng catchment in northern Thailand, road length was found to be the most important single variable leading to increased run-off and sediment yield (Pransutjarit 1983). In the Konto basin, East Java, roads occupy about 3% of the catchment but contribute disproportionately to the total sediment yield of the basin (Rijsdijk & Bruijnzeel 1991). Unsealed road and track surfaces have lower saturated hydraulic conductivities; higher bulk densities and fewer opportunities for percolation than the surrounding forest. On roads and tracks, overland flow occurs in every storm. Road surfaces are frequently rutted, providing opportunities for concentrated flow and entrainment of debris and eventually gully development. Repairs made by filling ruts and gullies provide loose material to the road surface, which easily becomes part of the sediment load carried by the next storm. Extensive soil disturbance by crawler tractors has been recorded frequently. Tractor paths were found to occupy 24.7% of a logging area in the Segaliud-Lohan area of Sabah, compared with 14% nine years earlier when lighter equipment was used (Fox 1969).

Details of the changes in road surface condition are provided by a study of soil properties along skid trails in Peninsular Malaysia two years after harvesting operations ceased (Kamaruzaman & Nik 1986; Kamaruzaman 1988). Bulk densities in the top 15 cm of the soil had increased by 54% on the tracks, by 37% between the tracks and by 24% on the berms pushed up at the outer edge of the tracks. Porosity was reduced by 20.4, 13.4 and 8.8%, respectively, while resistance to penetration increased by 10% on the tracks. Later studies in at Mendolong and Ulu Segama in Sabah confirmed the higher bulk densities on tracks (Malmer & Grip 1990; Van der Plas & Bruijnzeel 1993). At Mendolong, tractor tracks occupied a considerable proportion of the area being logged; 24%, as against 4% for the catchment where manual extraction was practised. Reduction in infiltrability in the mechanically harvested area resulted in greater slope run-off and soil loss. Most significantly, the work at Ulu Segama, Sabah showed that the impact of mechanized forest harvesting on topsoil characteristics was still apparent after 12 years of forest regeneration (Van der Plas & Bruijnzeel 1993). Roads may become part of the integrated ephemeral drainage network feeding water to streams during heavy storms, thus increasing the rate and magnitude of storm run-off.

A bounded plot (5 m × 1 m) on an abandoned logging track in Ulu Segama produced 96 t $ha^{-1} yr^{-1}$ in the period June 1989 to May 1990, 55% of which were eroded in the first two months after timber harvesting ceased (Sinun *et al*. 1992). However, the bounded nature of the plot, which prevented water from upslope contributing to the erosion meant that deep gullying did not occur (Douglas *et al*. 1995). Continuing studies in Ulu Segama (Douglas *et al*. 1999) showed that abandoned logging roads and tracks continued to yield sediment and to be subject to gullying, even where a vegetative canopy has developed over the bare soil, for at least five years after logging has ceased. Terrain conditions in Ulu Segama are not as steep as at Mendolong and the rocks tend to weather into more cohesive, clay-rich soils.

Between 1980 and 1988, FRIM's Bukit Berembun work (Baharuddin 1988) showed that carefully supervised harvesting could reduce the suspended sediment concentrations in streams. The recommended treatments included:

(i) alignment of logging roads along contours;
(ii) proper drainage for road run-off;
(iii) construction of cross-drains at 45–60° across logging roads;

(iv) installation of culverts or hollow logs at vehicular stream crossings;
(v) no logging within 20-m-wide stream buffer strips.

To these prescriptions, work in Ulu Segama has added the construction of water barriers (by bulldozing up earth mounds) across abandoned tractor tracks and reduction of the width of tracks and road clearings (Douglas *et al.* 1995). Breaking up the surface of abandoned tracks helps to encourage regeneration. Such simple treatments can greatly reduce the long-lasting effects of roads on catchment hydrology.

(c) *Using remote sensing to improve erosion risk estimates and minimize the environmental impact of forestry operations*

Planning of forestry operations to reduce their hydrological and erosional impacts requires an ability to move up to the management scale of tens and hundreds of square kilometres from the research catchment scale of a few hectares to 5 km or so. This upscaling of predictions requires detailed knowledge of terrain and land cover. Such information can now be brought together through remote sensing and the use of GIS.

The use of GIS for erosion risk modelling and assessment has been carried out on two scales: generalized and landscape. Generalized assessments are made at the macro-, often national, scale and are based largely on analysing climatic data or employ some measure of erosion intensity. For example, aerial photographs and Landsat satellite image data have been used to develop a dynamic model of the Nam Pong Basin in the north-east of Thailand (Johnson & Kolavalli 1984). The model simulates erosion that results from conversion of watershed land to alternative uses. In Indonesia, 1:50 000 scale aerial photographs were used to produce a semi-detailed soil erosion hazard map of part of Central Java at the same scale (Tukidal-Yunianto 1982). The soil erosion hazard factors were directly observed in the field and through laboratory tests of soil samples originating from each mapping unit. The soil erosion hazard was estimated from the standard USLE parameters including slope, soil erodibility, vegetative cover, and soil conservation practices. Aerial photograph interpretation facilitates the delineation of mapping unit boundaries based on terrain types.

Landscape studies of erosion modelling are carried out on a subcatchment level and usually involve some sort of discretization of the catchment into facets, zones or landscape units within which processes contributing to erosion can be modelled. Although GIS has been employed at each of these scales, the majority of research has been undertaken at a more detailed subcatchment scale. Digital terrain models are used in each of these studies as they provide a primary source of data from which topographic characteristics or the subcatchment zones can be derived according to some set of criteria or topographic index.

In South-East Asia land suitability assessments were used in conjunction with remote sensing and ground truth data to assess environmental degradation in the Komering River Catchment of Sumatra, and to evaluate how increased coffee cultivation in the headwaters would affect erosion and downstream channel changes and sedimentation. The Dutch integrated land and water management information system (Meijerink *et al.* 1988) has been widely used to prepare scenarios of actual and estimates future erosion. The high-grade facilities for analysing flow direction and accumulation in the system have been demonstrated to many government land agencies.

To be able to link ground truth on erosion to land cover characteristics derived from remote sensing, high-resolution imagery is required to define the gaps caused by forestry operations and roads and to distinguish forest of different ages of recovery from harvesting. While many general land cover and land use interpretations have been made using coarse resolution Advanced Very High Resolution Radiometer (AVHRR) information (Eiumnoh *et al.* 1997), the high-resolution Landsat and French Satellite Terrestrial Observation System (SPOT) imagery are need for accurate hydrological and erosion investigations. Such work has been developed as part of the German Technical Assistance (GTZ) programme in the Sabah Forest Department (Glauner 1999) and is underway as part of the collaborative Indicators of Forest Sustainability (INDFORSUS) project linking Indonesia, Malaysia, Thailand and Vietnam with European counterparts (Douglas 1998*b*). The latter involves making new erosion measurements under different types of land cover and terrain and acquiring new knowledge of the spectral, spatial and temporal characteristics of primary forest, secondary forests and forest plantation land cover under different management regimes. Particular challenges arise from the need to combine data collected at different spatial scales into a management-orientated database. Nevertheless, this work offers prospects of being able to apply the results of detailed hydrological research more directly in forest management.

5. CONCLUSION AND TASKS FOR THE FUTURE

Soil erosion is a natural process, but is greatly accelerated when forest disturbance exposes the soil to raindrop impact. While we know much about the way hydrological and earth surface processes work in individual forest research areas, we have difficulties in making reliable predictions at the scales at which forest managers work. Many technical ways of regulating water flows and reducing soil loss are well understood. Much less is known of why people use land in ways that cause erosion and land degradation. Research is needed on how the detailed plot and small catchment studies can be upscaled to larger units (Chappell *et al.*, this issue) where results can be used at the management scales of the annual logging coupes and for integrated catchment management. Little work has been done on the effectiveness of management responses, such as the building of water bars across logging tracks, or to determine the appropriate spacing of cross-drains on logging roads of a specified gradient on a particular type of parent material. Such practical, applied studies are urgently needed to ensure that the suggested remedies achieve the erosion mitigation for which they are designed. Ideally, the existing catchment studies which have already examined the initial phase of selective logging should be maintained to investigate the effectiveness of road treatments and reduced impact logging systems. Every effort should be made to integrate experiments in forest management techniques with appropriate hydrological and erosion investigations.

South-East Asia really needs some well-supported, long-term, experimental catchments studies, one in the volcanic terrain, one in the Tertiary mudstone-dominated sediments, and one on the older rocks of the Asian mainland, where the alternative management strategies can be tested. There is insufficient ground truth to use powerful modelling techniques accurately. The data for modelling will only be gathered if there is an integrated international effort, building on the work already done under such initiatives as the ASEAN–US Watershed Management Programme, to concentrate sufficient resources and scientific input in integrated studies at adequately financed sites.

At the same time, more needs to be done to analyse the wide range of data already collected, to continue to improve guidelines for forest management and to work with all those who have a stake in the future of South-East Asian forests. Any solutions to water, soil erosion and sedimentation problems in South-East Asian tropical forests must involve close collaboration with the people actually using the land. The political and legal factors affecting those people cannot be ignored. Forest workers, dwellers, shifting cultivators and marginal farmers have an interest in the future of the forest but often lack the security of job or land tenure which may make them more interested in the sustainable future of the forest. This is paper A/301 of the Royal Society South-East Asia Rain Forest Research Programme.

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