Malaysian forestry guidelines for mitigating water quality impacts in rainforests: implications from 20 years of local hydrological science

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Abstract

Many tropical rivers are experiencing large and rapid changes in their water quality. Quantifying those features of the disturbed tropical forest landscape that are the dominant sources of sediment or agro-chemicals requires local hydrological research if commercially-viable forestry practices are to be modified to maintain water quality. The findings presented illustrate how hydrological research in Malaysia is able to quantify the dominant sources of river sediments in areas disturbed by commercial tropical forestry. This is integrated with a discussion of the ways that so-called 'Reduced Impact Logging' practices in Malaysia can be used to mitigate the worst hydrological impacts.

Importance of suspended sediment delivery from tropical rainforests?

Selection felling, unlike clear-felling, is where only large commercial trees are cut and the forest allowed to regenerate. If all of the hydrological impacts of commercial selection felling in the tropics are compared, then it is sediment yield of rivers that changes the most from the natural state (Chappell *et al*., 2004a). The resultant input of sediments into streams 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). The mitigation of these deleterious impacts, therefore, should be central to the goal of sustainable management of natural forests within the tropics (Bruijnzeel, 1992).

What is the magnitude of change?

Very few catchment studies have examined the effect of tropical selective forestry on water-quality (Bruinjzeel, 1996), 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 datasets (Bruinjzeel, 1996) further limits the choice of published results for examination. In particular, Douglas *et al*. (1992) note that where tropical sediment budgets have not been derived from data collected by automatic storm sampling equipment, high-flow concentrations will be inadequately characterised and budgets under-estimated.

Generalisation of the catchment-scale impacts of different practices of selection or 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, Malaysia (Table 1). These studies indicate that the delivery of suspended-sediments may increase by 4–50 fold in the periods of road construction and subsequent selective timber harvesting. The limited catchment-scale data available makes explanation of the 10-fold range difficult, making the need for new studies to quantify which sediment sources are responsible for changes to catchment-scale sediment yield.

The 721 km^2 Ulu Segama catchment in Sabah, East Malaysia is gauged near the Baru and Jauh micro-catchments shown in Table 1. The annual suspended-sediment yield for this much larger basin is 306 t km^{-2} yr^{-1} and was derived from daily riverflow and concentration data from 1989 to 1996. This rate results from the history of selective-logging of over 400 km^2 of the southern headwaters primarily in the 1970s, and a second phase harvesting of a further 16 km^2 in 1993. As this scale contains annual logging coupes spanning tens of years and, thus, terrain at a range of stages from road construction to

Table 1 *Selective forestry impacts on catchment-scale suspended-sediment delivery during the harvesting phase of tropical natural forests. All datasets with high time-resolution sediment data are cited.*

*Study** *Name*	*1* *Baru*	*2* *Jauh*	*3* *Batangsi; Chongkak*	*4* *Lawing*
Size (km²)	0.44	1.5	19.9; 12.7	4.7
Location	E. Malaysia	E. Malaysia	W. Malaysia	W. Malaysia
Geology	siltstone	serpentinite	granite	granite
Practice	Conv[+]	RIL[++]	Conv	-
Disturbed**	1,600	431	2,826; 2,476	1,389
Control**	300	100	54	-
Difference	+ 5.3 fold	+4.3 fold	+52; 46 fold	+20 fold

* 1: Douglas et al. (1992) and Greer et al. (1996); 2: Douglas and Bidin (1994), 3: Lai (1992); 4: Lai et al. (1999); [+] Conventional selective logging; [++] Reduced Impact Logging; ** sediment yield in t km^{-2} yr^{-1}; [a] Moura-Costa and Karolus (1992); [b] bedload also measured

recovery with persistent impacts, it probably provides a better estimate of sediment flux than do the results of small experimental catchments, such as those presented in Table 1. It should be remembered, however, that with increasing scale generally comes a reduction in mean channel slope and, therefore, an increase in the in-channel storage or residence time of the sediment (Dietrich and Dunne, 1978). This may damp and prolong the local effects associated with individual forest management coupes.

A key issue that needs to be addressed at the catchment scale is the degree to which Reduced Impact Logging (RIL) methods developed in Malaysia (Pinard *et al.,* 1995; MTCC, 2004) can mitigate the water quality impacts observed in Malaysia following conventional, unsupervised methods of selective felling. For timber to be imported into the UK, it must have been cut by RIL methods and a certificate issued by an independent assessor (e.g., SGS, SIRIM).

Sediment sources and mitigation measures?

The localised nature of sediment sources such as landslides and culvert collapses (Douglas *et al*., 1992; Walsh et al., 2006), combined with the episodic nature of the sediment delivery (Douglas *et al*., 1999) means that the amount of sediment reaching streams from sources of erosion or mass movement cannot be accurately predicted from visual observations. This is, however, the normal practice during certification of forest management systems. Equally, the extreme localisation of sediment delivery in time and space means that landscape-scale erosion and mass movement should not be simulated by models unless good stream sediment data are available for distributed validation.

Road sources and mitigation

Research conducted six years following the first phase of commercial harvesting in the Ulu Segama Forest Reserve (Sabah) shows that log culvert failure and slips within cut-and-fill sections of a surfaced, secondary haulage road were responsible for most sediment moving from a 0.44 km² study area (Chappell *et al*., 2004b). Sidle *et al*. (2004) and Gomi *et al*. (2006) did not collect turbidity data for the streams within the Bukit Tarek catchment in West Malaysia but their investigations along the roads and skid trails did indicate the dominant role of roads in sediment delivery. It is obvious that most roads within forest and agricultural landscapes cannot be built to the standards of highways with a tarred surface, concrete culverts and slope protection. Main and secondary forest roads within Malaysia are however constructed to a high standard because failure during harvesting a sequence of coupes would lead to considerable economic impact for the forestry operations. Semi-quantitative observations of the location and design of main and secondary forest roads within the Ulu Segama Forest Reserve (FR) would indicate that the roads are well built, with correct grades, proximity to ridge tops, etc. (see e.g. Figure 1). These same observations show that some hollow-log culverts and sections of cut-and-fill roads can collapse within ten years of construction (Figure 1). These were the dominant sources of suspended sediment within the Baru catchment during the recovery phase. Unfortunately, the general lack of combined stream turbidity and flow measurements within most tropical studies allows little assessment of sediment benefits of different road designs.

Skidder-trail sources and mitigation

The bright orange colour of exposed tropical subsoil, combined with yarding logs from the stump to a log landing using tracked ‘skidder’ vehicles, produces a very visible network of trails. Along skid trails, local changes to the soil hydraulic properties of bulk density and permeability have been clearly demonstrated in the Malaysian studies of Malmer and Grip (1990) and Pinard *et al*. (2000). From the hydrologists’ perspective the main question is whether the localised zones of low permeability along tracks are sufficiently well connected with the streams (see Sidle *et al*., 2004) and sufficiently extensive to allow: (a) large volumes of infiltration-excess overland flow to enter the streams, and (b) allow fine sediments to be washed from skid trails (and un-surfaced feeder roads) into streams. Within the Baru catchment, the data-based modelling study of Chappell *et al*. (2006a) suggests that

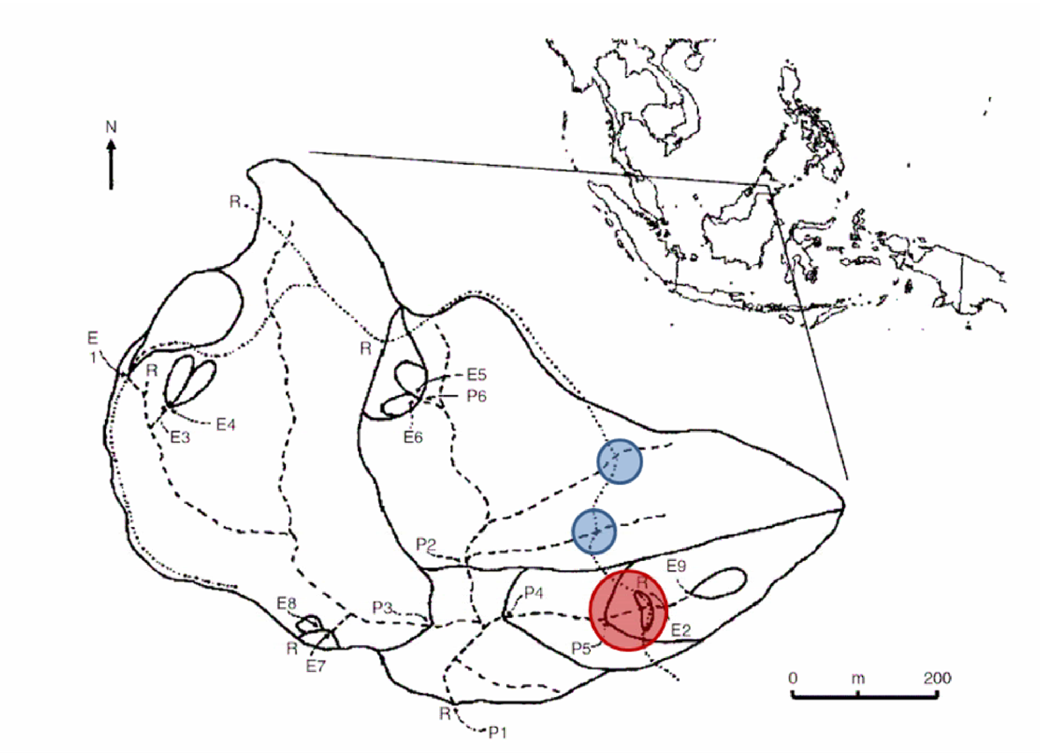

Figure 1 *Location of the single secondary haulage road and single feeder road (dotted lines) in the Baru ExperimentalCatchment with respect of the streams (first-, second- and third-order: dashed lines). The feeder road is located on the western boundary of the catchment. The blue circles show the location of the hollow-log culvert collapses, while the red circle shows the location of the P4 landslide. Numbers refer to the rainfall (R) and surface flow (E/P) gauging stations*

the road/trail networks may not be extensive enough to affect the hydrograph of a third-order stream, although visual observations in the same catchment of fines draping coarse channel sediments shortly after harvesting activities indicates that even small amounts of overland flow allows fines to reach streams.

Plot-scale studies within the 4 km^2 Sapat Kalisun catchment (that contains the Baru catchment) show that grasses soon colonise skid trails and unsurfaced feeder roads following the cessation of logging and effectively halt surface erosion (Douglas *et al*., 1995). The absence of fine particles draping coarse channel sediments only five years post harvesting of the same area, supports the plot-scale measurements of terrain recovery. These measurements and visual observations came from an area affected by 'conventional' selective logging (Coupe 88/89 of the Ulu Segama FR), rather than selective felling areas certified as 'well managed' by international, independent assessors. Consequently, new experimental studies to judge the effect of reduced numbers of skid trails on sediment yield under such certified RIL systems would be of value, as would a hydrological comparison of other yarding systems such as helicopter or skyline use.

Channel sources and mitigation

Because of the greater frequency of lower-order watercourses within any landscape, including the tropics (Table 2), most riverflow has entered the channel network through the bed and banks of small streams, namely first- to third-order streams (see Figure 1). Consequently, first- to third- order streams are a hydrologically more sensitive part of the landscape than rivers. Zero-order or ephemeral channels, which by definition only flow during rainstorms, might be considered less active parts of the landscape than small perennial channels because they carry a smaller proportion of the rainfall per unit area (Chappell *et al*., 1999).

Within undisturbed natural forests in many areas of the humid tropics, erosion and collapse of the banks of perennial channels is a central component of the sediment yield of rivers (Douglas *et al*., 1999). Channel banks along perennial channels are sensitive because they remain wet (and hence less stable) and are continually acted upon by moving water. Equally, Chappell *et al*. (2004b), working within the Baru catchment using 15 turbidity and flow measuring stations, showed that the greater sediment

Table 2 *Drainage density within the Sapat Kalisun catchment, Ulu Segama FR, Sabah, East Malaysia*

Stream type	*Drainage density (km/km^2)*	*Drainage density normalised for deep seepage$^+$ (km/km^2)*
First-order*	5.4	4
Second-order*	1.3	1.3
Third-order*	0.3	0.3
Fourth-order	0.3	0.3

*from Baru sub-catchment; $^+$corrected for stream reaches where Q < P + E due to deep seepage production per unit area (impacting downstream) in disturbed forest is from the first- to third-order streams. Some sic years post-harvesting the zero-order / ephemeral channels generated much less sediment per unit area. The effects of disturbance to soils at some distance from the perennial channels are less likely to reach the active channels compared to disturbances near to channels. Thus, major rivers are naturally more protected from localised erosion or mass movement in some distal parts of the landscape. Consequently, minimising soil disturbance along permanent channels and within a few metres of these channels would have a much greater impact on downstream sediment loads than any measures adopted at some distance from these channels. Within many tropical areas, specific measures are not applied to protect these smaller perennial streams. The FAO and Australian guidelines (Sist *et al*., 1998) do not require formal 'buffer zones' along permanent streams that have a channel width of less than 5 m. In many humid tropical areas, the key first- to third-order channels are less than 5 m wide and thus do not have buffer zones and are, therefore, totally unprotected. McIntosh and Laffan (2005) have suggested that this lack of protection of small permanent streams would mean that sediments would enter major rivers along these small streams and effectively 'short circuit' the buffer zones on large rivers. In contast, within certified natural forests in Peninsular Malaysia, buffer zones have to be placed on all permanent channels and within these zones all harvesting is prohibited and managed road/trail crossings are required (MTCC, 2001, 2004). This adopted measure of hydrological protection is therefore, consistent with the latest hydrological evidence from Sabah, East Malaysia (Thang and Chappell, 2004).

There is currently much academic debate over the required width of designated buffer zones. This is a complex issue in that stream buffers may be defined for different purposes, e.g. wildlife corridors, aquatic habitat, seed banks, soil protection, overland flow protection, or as sediment traps. Even where the hydrological criteria are considered in isolation, namely soil protection, overland flow protection and sediment traps, there is still much debate. Questions have been raised regarding the effectiveness of buffers, even 50 m wide, for trapping sediment in tropical areas (Ziegler *et al*., 2006). Indeed, Table 3 shows that major landslides within the Baru catchment are not halted by the presence of streamside trees. If hydrological criteria are used for defining buffer width, e.g. extent of near-saturated soils, there are still problems, as such areas are difficult to predict within managed tropical forests (Bren, 2000; Chappell *et al*., 2006b). This is a key area where new hydrological research is needed, not only for natural forest management, but also for stream protection from applied pesticides and fertilizers within areas newly planted with oil palm (MTCC, 2007).

Table 3 *Mean lengths from haulage roads to permanent streams and travel distance of two road initiated landslides on 19th January 1996 for the Baru experimental watershed, Ulu Segama Forest Reserve, East Malaysia*

1st order streams	87 m
2nd order streams	158 m
3rd order streams	255 m
P4 landslide (19/1/96)	150 m
Divide landslide (19/1/96)	500 m

A key issue when considering the designation of stream buffer zones is the economic cost of prohibiting or limiting harvesting in a certain area, or requiring extra planning or greater on-site supervision (Tay *et al*., 2001). The 5 m wide buffers on all permanent streams in certified forests in Peninsular Malaysia, if applied to areas with a similar drainage density to the Baru catchment, would place only 6% of the region in a stream buffer zone. Other authors (e.g. Durst, 1999; Cassells and Bruijnzeel, 2004), however, have suggested that 20 m wide buffers should be placed on all channels, including ephemeral channels. If this rule were applied within the same area, some 40% of the region would fall into a buffer zone and most likely fail the economic criterion of 'sustainability' for forest management.

Conclusions

Despite the recent intensification of hydrological research within tropical, natural forests (Bonell and Bruijnzeel, 2004), the impact of many forestry practices on tropical hydrological systems remain poorly quantified. Amounts and sources of river sediments in particular are extremely difficult to determine with accuracy because of the episodic nature of sediment delivery, the heterogeneity of the sediment sources and the high technological requirements for such measurements (Douglas *et al*., 1999). Despite these uncertainties, it is clear that small permanent streams, because they comprise the greatest length of perennial watercourse and receive the greatest sediment inputs per unit watershed area, should now be protected within tropical forests certified as 'well managed' (Chappell and Thang, 2007) as a priority.

While few studies have addressed the water quality impacts of forestry within tropical natural forests and associated mitigation strategies, almost none have addressed river turbidity for tropical plantations such as oil palm (Chappell *et al*., 2007). There is an urgent need to extrapolate the findings of turbidity studies from tropical natural forests to watersheds with plantations, and to initiate new watershed-scale studies on all aspects of water quality within timber and oil-palm plantations. This hydrological research needs to include the economic impacts of maintaining buffer zones of different sizes within areas being converted to timber plantations and agro-forestry systems.

The UK population benefits from oil palm and timber products from tropical countries such as Malaysia. There is an equal opportunity for these countries to benefit from assistance from the UK hydrological community if we are willing to address these key research questions.

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