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Practical hydrological protection of tropical forests: Malaysia's scientific contribution

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Abstract

Malaysian scientists are making a global impact in the discipline of tropical forest hydrology. Recent hydrological research conducted within Sabah and other Malaysian states has the potential to provide new scientific evidence to further underpin Malaysia's reputation in developing methods of 'reduced impact logging' and forest management certification. This academic synthesis addresses the forestry relevance of local hydrological research on quantifying and mitigating the affects of canopy disturbance, road construction, ground skidding, disturbance to nutrients and disturbance to the water-courses. Greater collaboration between the hydrologists and foresters can only support efforts to enhance the social, economic and environmental services offered by tropical forests.

Introduction

Malaysia's contribution to hydrological research within tropical forests is exemplary, possibly the best of any nation, and this explains why UNESCO-IHP chose Malaysia to host their 10-year review of the status of research on tropical forest hydrology (Bonell and Bruijnzeel, 2004). From a hydrologist's perspective, Malaysia is also a leader in developing guidelines to mitigate the adverse impacts of forestland utilisation on tropical water resources.

Tropical forest hydrology is the scientific study of water resources from the effects of forests on climate, the soil-water and hence nutrient system, the pathways of water, solutes and eroded-particles to streams and the behaviour of rivers. Consequently, forestry's potential effects on hydrological processes might impact on many other environmental services. Forests both natural and planted are also a major economic and social resource, so any methods of mitigating the (potentially) negative hydrological impacts of forestry must be practical and maintain a viable forestry industry. Quantifying environmental (hydrological) change, attributing the causes of change and then identifying a small number of practical mitigation measures is a most demanding research topic requiring robust modelling and critically, large volumes of high quality field data. These data are increasingly available for natural forests in Malaysia. The availability of these data means that other sectors of the economy with a 'water footprint' namely plantation, agricultural, industrial and construction sectors could benefit from any new findings.

In the last 20 years, a huge number of tropical forestry guidelines have been developed that include hydrological protection. Invariably, these measures have been devised by foresters and ecologists needing to consider the whole forest system (Thang Hooi Chiew, 1987; Dykstra & Heinrich, 1996; Sabah Forest Department, 1998; Sist, Dykstra & Fimbal, 1998; Durst, 1999; MTCC, 2001). Despite the fundamental role of water in forest management, very few hydrologists have been directly involved in supporting foresters with guideline development or evaluation.

Within this short contribution we aim to highlight new hydrological findings particularly from Malaysia's forests that quantify those hydrological changes impacting at landscape scales, link these impacts to particular forestry operations and finally evaluate whether suggested or applied forestry standards address these hydrological phenomena. This work is a development of ideas arising from a UNESCO-IHP review of hydrological change in selectively-managed forests (Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004) and an evaluation of the MC&I for Peninsular Malaysia (Thang Hooi Chiew and Chappell, 2004; Chappell and Thang Hooi Chiew, 2008). However, we give greater emphasis to the hydrological research findings from Sabah and guidelines for hydrological protection pertinent to the state (e.g., Sabah Forestry Department, 1998; MTCC, 2001, 2004; Hasse & Camphausen, 2007). In the interests of simplification of the potential impacts of forestry on complex hydrological systems, we divide the analysis into four key types of potential impact, namely effects of canopy disturbance, road construction, use of skidders, disturbance to nutrients and disturbance to the water-courses. While we focus on the scientific evidence, we do realise that other hydrologists may arrive at different interpretations from the same primary data. Given consideration of length, we focus only on the 'negative' impacts of forestry, but encourage the reader to look at publications providing scientific evidence for the 'positive' hydrological impacts of managed forests (e.g., Bolstad & Swank, 1997; Chappell, 2006; Chappell, Tych & Bonell, 2007).

I. Canopy disturbance and mitigation

Removal of trees during commercial rainforest harvesting reduces the quantity of wet canopy evaporation and transpiration. Reduced Impact Logging (RIL) or supervised harvesting has been shown in the Bukit Berembun catchments (Negeri Sembilan) to reduce the change from the natural state (Abdul Rahim Nik and Harding, 1992; Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004). This is because RIL (Sabah Forestry Department, 1998) significantly reduces the amount of collateral damage to the remaining canopy, as shown by the studies of Pinard & Putz (1996) in the RIL test area of the Yayasan Sabah concession. As wet canopy evaporation and transpiration reduce, hydrologists working at small catchment scales (i.e., < 50 km^2) demonstrate an equal increase in river discharge because rainfall impacts are not apparent at this small scale (Bruijnzeel, 1996). Some hydrologists suggest that forests should be cleared to gain the extra water resources in rivers (NR-International, 2005), however this view is not universally supported because of the other impacts on water (Chappell & Bonell, 2005).

Recent analysis of the same records for the Bukit Berembun catchments shows that at this small scale, forestry operations can increase stream peak-flows, though the flashiness of the stream behaviour may reduce where RIL methods are used (Table 1: from Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004). Work in Malaysia suggests that the peak-flow increases immediately after harvesting relate to the changes in evapo-transpiration (Kawi Bidin and Chappell, 2004), rather than the roads having a significant impact on the volume of water entering streams as overland flow. A recent data-based modelling analysis of the Baru catchment within the Yayasan Sabah forest concession shows only very small changes in the overland flow volumes resulting from forest roads and skid trails (Chappell, Tych, Chotai, Kawi Bidin, Waidi Sinun, & Thang Hooi Chiew, 2006). While there is little robust evidence at the large scale (i.e., > 1000 km^2) of the positive effects of forest presence on mitigating river flooding, dismissing this possibility (FAO, 2005; Calder and Aylward, 2006) is equally without scientific evidence (Chappell, 2006). Furthermore, removal of forest biomass over millions of hectares may have a significant impact on the generation of local convective rainfall cells (Wan Azli Wan Hassan, 1999; Voldoire & Royer, 2005), though rainfall simulations within Regional or Global Climate Models are currently unreliable (Fowell, 2006).

Table 1. Changes in (a) stream peakflow and (b) flashiness within the Bukit Berembun Experimental Catchments, Negeri Sembilan, Malaysia (adapted from Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004).

(a) Daily riverflow (mm/d) equalled or exceed for 10 % of the time (Q10 statistic describing highflows)

	C1 Unsupervised 13.3 ha	C2 control 4.6 ha	C3 RIL logging 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	increase	reduce	increase
period	1.430 fold	0.938 fold	1.090 fold
Logging and Recovery (1984-5)	1.5224	1.6001	1.9706
relative change from 1981-2	increase	increase	increase
period	1.045 fold	1.051 fold	1.232 fold

(b) Q30/Q70 river flashiness statistics where flows in the ‘flow duration curves’ are normalised by the respective mean daily flows (MDF)

	C1 Unsupervised 13.3 ha	C2 control 4.6 ha	C3 RIL logging 30.8 ha
Pre. Logging (1981-2)	1.9815 [a]	1.9568 [a]	2.6905 [a]
difference to 'control'	0.0247	-	0.7337
direction of difference	same	-	much more flashy
Logging and Recovery (1984-5)	2.2039	1.9545	2.4851
absolute change [b]	0.2214	0.0023	0.2054
direction of change	slightly more flashy	same	slightly less flashy
Logging and Recovery (1984-8)	1.9390	1.9524	2.1783
absolute change [b]	0.0425	0.0044	0.5122
direction of change	same	same	much less flashy

[a] a greater value indicates an increase in 'streamflow 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

II. Road impact and mitigation

If all of the hydrological impacts of commercial selection felling are compared, then it is sediment yield of rivers that changes the most from the natural state (Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004). The impact of forest management on the amount of sediment delivered downstream can be assessed accurately only by measuring the streamflow and sediment concentration at the same time and location. The localised nature of sediment sources such as landslides and culvert collapses, combined with the episodic nature of the sediment delivery (Douglas, Kawi Bidin, Balamurugan Gurusamy, Chappell, Walsh, Greer, & Waidi Sinun, 1999) means that the amount of sediment reaching streams from sources of erosion or mass movement cannot be accurately predicted from visual observations. Equally, this extreme localisation of sediment delivery in time and space means that landscape-scale erosion and mass movement should not be predicted by models unless good stream sediment data are available for validation.

Research conducted 6 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 km^2 study area (Chappell, Douglas, Mohd Jamil Hanapi & Tych, 2004). While turbidity data for the stream within the Bukit Tarek catchment (Selangor) studied by Sidle, Sasaki, Otsuki, Noguchi, & Abd Rahim Nik (2004) and Gomi, Sidle, Noguchi, Negishi, Abdul Rahim Nik & Sasaki (2006) was not collected, their investigations along the roads and skid trails indicated 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 (Forestry Department Peninsular Malaysia, 1999; Sabah Forestry Department, 1998) 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 would indicate that the roads are built well with correct grades, proximity to ridge tops etc (see e.g., Figure 1). These same observations show that some log culverts on secondary roads could collapse within 10 years of construction. Perhaps the economic costs and benefits of using non-timber culverts for secondary roads could be assessed. Unfortunately, the lack of combined stream turbidity and flow measurements, with the exception of a few isolated studies in Selangor (e.g., Lai Food See, 1992; Lai Food See & S. Detphachanh, 2006), Negeri Sembilan (Zulkifli Yusop & Anhar Suki, 1994), and Sabah (Douglas, Spencer, Greer, Kawi Bidin, Waidi Sinun & Wong Wai Meng, 1992; Douglas, Kawi Bidin, G. Balamurgan, Chappell, Walsh, Greer, & Waidi Sinun, 1999; Chappell, Douglas, Mohd Jamil Hanapi & Tych, 2004), allows little assessment of sediment benefits of different road designs. This is not a problem specific to Malaysia, as Malaysia’s few data-series are probably the best for small forest catchments anywhere in the tropics.

III. Skidder impact and mitigation

The bright orange colour of exposed tropical subsoils combined with yarding logs from the stump to a log landing using skidders produces a very visible network of tracks. Along skid trails, local changes to the soil hydraulic properties of bulk density and permeability have been clearly demonstrated in the Sabah-based studies of Malmer and Grip (1990), Waidi Sinun, Wong Wai Meng, Douglas & Spencer (1992), Van der Plas & Bruijnzeel (1993), and Pinard, Barker & John Tay (2000). Indeed, these studies are widely cited in the global hydrology literature. Along well used skid trails (and log landings), the local influences soil hydraulic properties and nutrient status affect the rate of regeneration of commercial timber trees (Nussbaum, Anderson & Spencer, 1995). Within Sabah, the RIL rules do however mitigate this impact by requiring ripping of all log landings post harvest (Sabah Forest Department, 1998).

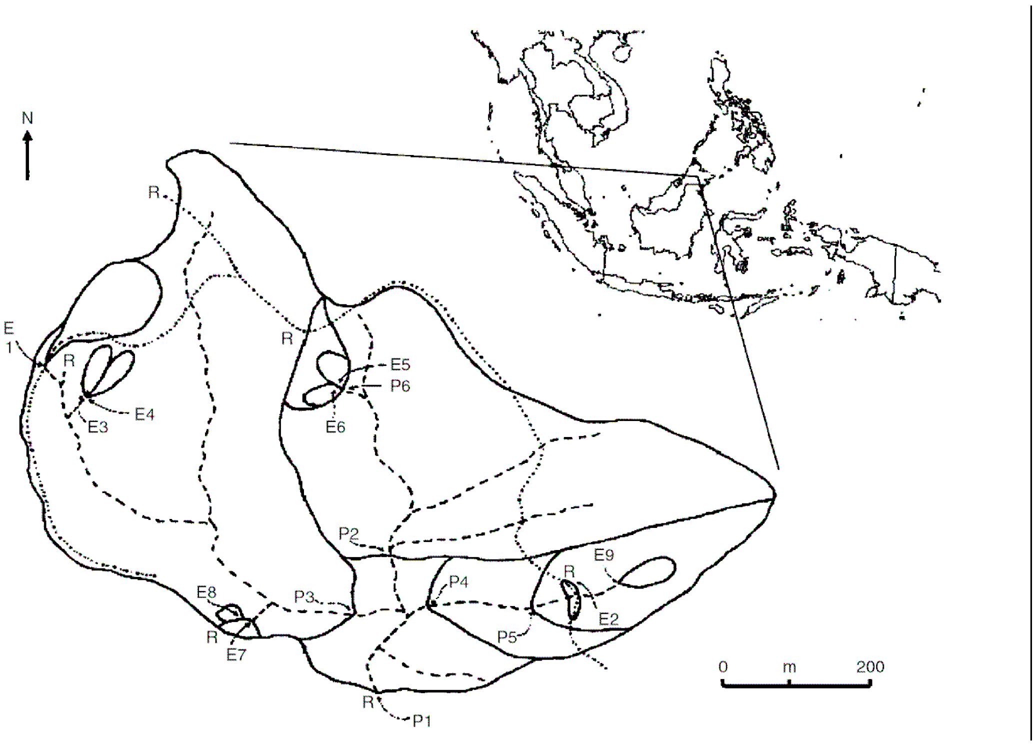

Figure 1. Location of the single secondary haulage road and single feeder road (dotted lines) in the Baru Experimental Catchment with respect of the streams (first-, second- and third-order: dashed lines). The feeder road is located on the western boundary of the catchment. The summit of Bukit Baru (255 m) is at the eastern corner of the basin. Numbers refer to the rainfall (R) and surface flow (E/P) gauging stations. Adapted from Chappell, Douglas, Mohd Jamil Hanapi & Tych (2004).

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, Sasaki, Otsuki, Noguchi, & Abd Rahim Nik, 2004) and sufficiently extensive to allow a) large volumes of 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 (Sabah) the study of Chappell, Tych, Chotai, Kawi Bidin, Waidi Sinun, & Thang Hooi Chiew (2006) suggests that the road/trail networks may not be extensive enough to affect the hydrograph of a third-order stream, however, visual observations of fines draping coarse channel sediments shortly after harvesting activities indicates that fines can reach the streams.

Plot-scale studies within the Sapat Kalisun Catchment (near the Danum Valley Field Centre, Ulu Segama FR) show that grasses soon colonise skid trails and un-surfaced feeder roads and effectively halt surface erosion (Douglas, Greer, Waidi Sinun, Anderton, Kawi Bidin, Spilsbury, Jadda Suhaimi & Azman Sulaiman, 1995; Chappell, McKenna, Kawi Bidin, Douglas & Walsh, 1999; Pinard, Barker & John Tay, 2000). The absence of fine particles draping coarse channel sediments only 5 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 certified by international, independent assessors as with the Deramakot FR (SGS, 2004; Peter Lagan, Sam Mannan & Matsubayashi, 2007). Consequently, new experimental studies to judge the effect of skid trails on river sediments under certified RIL systems (e.g., Sabah Forest Department, 1998; MTCC, 2001, 2004) would be of value, as would a hydrological comparison of other yarding systems such as helicopter or skyline use (Peter Lagan, Sam Mannan & Matsubayashi, 2007)

IV. Disturbance to nutrients and mitigation

During tropical forest harvesting, the removal of part of the vegetation, the increases of infiltration and soil-water (due to reduced wet canopy evaporation and transpiration) and disturbance of the topsoil have the potential to increase nutrient losses to rivers. Quantification of these impacts within tropical forests is however hampered by a lack of detailed studies. Three of the best nutrient studies in the humid tropical forests have been conducted in Negeri Sembilan (Bukit Berembun: Zulkifili Yusop, 1989), Selangor (Bukit Tarek: Zulkifli Yusop, Douglas & Abdul Rahim Nik, 2006) and Sabah (Sipitang: Nykvist, Grip, Sim, Malmer & F.K Wong, 1994). As with sediment yield, the problem of generalisation from so few tropical studies is acute. What is clear from the Malaysian studies however is the rapid recovery of the levels of some nutrients, e.g., nitrogen, within streams (Malmer, 1996) and the smaller losses from RIL systems with their reduced canopy and ground disturbance (Table 2: Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004). It should be noted that nutrient levels within streams of disturbed natural forests remain magnitudes lower than levels within agricultural or urban streams.

V. Channel disturbance and mitigation

Permanent (or perennial) stream channels as their name suggests have flow throughout the year. The smallest of these permanent streams is called a 'first-order stream'. Once two of these streams join, they become a 'second-order stream', two second-order streams joining become a 'third-order stream' and so on (Strahler, 1952). Within the Brassey Range of uplands in the interior of Sabah, fourth-order streams can have a width of more than 5 metres and might be called small rivers. Because of the greater frequency of lower-order water-courses within the landscape (Table 3), 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. The ephemeral channels which by definition only flow during rainstorms (Dingman, 1994) might be considered less active parts of the landscape (Thang and Chappell, 2004) because they carry only a small proportion of the rainfall per unit area (Chappell, McKenna, Kawi Bidin, Douglas & Walsh, 1999). Intermittent channels are not common within the a-seasonal parts of the equatorial tropics. As a result of the steep channel slopes in headwaters any water, sediment or solute that enters this active first- to third-order channel network is rapidly transported downstream.

Table 2. Accelerated macro-nutrient flux from the Bukit Berembun rivers following selective timber harvesting (adapted from Chappell, Tych, Zulkifli Yusop, Abd Rahim Nik, & Baharuddin Kasran, 2004).

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]	+ 2.0 fold NO_3
	+ 3.0 fold PO_4	+ 2.3 fold PO_4
	+ 2.4 fold K^+	+ 2.1 fold K^+
	+ 1.8 fold Ca^{2+}	+ 1.8 fold Ca^{2+}
	+ 1.7 fold Mg^{2+}	+ 1.8 fold Mg^{2+}
C3 (closely supervised) [a]	+ 2.1 fold NO_3	+ 1.6 fold NO_3
	+ 1.2 fold PO_4	+ 1.5 fold PO_4
	+ 1.3 fold K^{2+}	+ 1.2 fold K^{2+}
	+ 1.3 fold Ca^{2+}	+ 1.2 fold Ca^{2+}
	+ 1.4 fold Mg^{2+}	+ 1.1 fold Mg^{2+}

[a] 'Commercial logging' is also known as 'conventional' or 'unsupervised' selective logging, while, 'closely supervised logging' is also known as 'Reducted Impact Logging (RIL)'. [b] macro-nutrient flux is equivalent to nutrient load. c increase in the flow of dissolved macro-nutrients (nitrate, phosphate, potassium, calcium and magnesium) over the Bukit Berembun river gauging structures within C1 and C3 relative to that in C2, the control catchment. Some bias may be incorporated due to natural differences between the control and other catchments.

Within undisturbed natural forests in the tropics, erosion and collapse of the banks of perennial channels is a central component of the sediment yield of rivers. This finding is true for a monitored catchment within the Class I forest reserve of the Danum Valley Conservation Area (Balamurugan Gurusamy, 1997; Douglas, Kawi Bidin, Balamurugan Gurusamy, Chappell, Walsh, Greer, & Waidi Sinun, 1999). Channel banks are sensitive because they remain wet (and hence less stable: Chappell, Ternan & Kawi Bidin, 1999) and are continually acted upon by moving water. The banks and bed of perennial streams are likely to remain a geomorphologically (i.e., erosion and mass movement processes) sensitive part of the landscape within natural forests disturbed by forestry operations. Indeed the recent research of Chappell, Douglas, Mohd Jamil Hanapi & Tych (2004) within the Baru catchment (Sabah) uses 15 turbidity and flow measuring stations to show that the greater sediment production per unit area (impacting downstream) is from first- to third-order streams. During this recovery phase some 6 years post-harvesting the 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 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 certified natural forests in Peninsular Malaysia a 5 m wide buffer zone is designated either side of all permanent channels and within this area all harvesting is prohibited and managed road/trail crossings are required (MTCC, 2001, 2004). This measure of hydrological protection is therefore consistent with the latest hydrological evidence from Sabah (Thang Hooi Chiew & Chappell, 2004, Chappell & Thang Hooi Chiew, 2008). Within many tropical areas, specific measures are not applied to protect these smaller perennial streams. The FAO and Australian guidelines (Cassells, Gilmour & Bonell, 1984; Sist, Dykstra & Fimbel, 1998) do not require formal ‘buffer zones’ along permanent streams that have a channel width of less than 5 m. McIntosh & 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. Sabah currently utilises a designation for ‘buffer zones’ similar to the FAO system, however RIL rules do explicitly prohibit the use of permanent water-courses as routes for skidders (Section 2.1.5: Sabah Forest Department, 1998). This rule may be an effective way of protecting the first- to third-order channels.

Table 3. Drainage density within the Sapat Kalisun catchment, Ulu Segama FR, Sabah

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, as shown in Chappell, McKenna, Kawi Bidin, Douglas & Walsh (1999)

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 (Ziegler, Tran, Giambelluca, Sidle, Sutherland, Nullet, & Tran, 2006). Indeed, Table 4 (from Chappell and Thang Hooi Chiew, 2008) shows that major landslides within the Sapat Kalisun catchment are not halted by the presence of streamside trees (Walsh, Clarke, Kawi Bidin, Blake, Chappell, Douglas, Nazri Ramli, Sayer, Waidi Sinun, Johnny Larenus and Mohd Jamil Hanapi, 2006). Furthermore, there are many questions regarding the best way to predict the patterns of soil saturation in streamside areas for soil and overland flow protection (Bren, 2000; Mui-How Phua & Minowa, 2005; Chappell, Vongtanaboon & Jiang, 2006). 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 tropical plantations (MTCC, 2007).

Table 4. 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 (adapted from Chappell and Thang Hooi Chiew, 2008)

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 costs of prohibiting or limiting harvesting in a certain area, or requiring extra planning or greater on-site supervision (John Tay, Healey & Price, 2001; Sam Mannan, Yahya Awang, Albert Radin, Andurus Abi, & Peter Lagan, 2002). Thang Hooi Chiew & Chappell (2004) calculated that the 5 m wide buffers on all permanent streams 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) have suggested that 20 m wide buffers should be placed on all channels, including ephemeral channels. Thang Hooi Chiew & Chappell (2004) calculated that if this rule were applied within the same area, some 40 % of the region would fall into a buffer zone; this would most likely fail the economic criterion of sustainable forest management.

Conclusion

Malaysian hydrologists, ecologists and foresters have been conducting fundamental hydrological research within tropical forests that is of global significance. The contributions of the Malaysian federal and state governments and their agencies have played a crucial role in supporting this science. The new hydrological findings that have resulted have the potential to support foresters in their continued refinement of measures to enhance the economic and environmental services of Malaysia's forests. Many academic challenges remain for the tropical forest hydrologist, and considerable mutual benefit can be gained from greater collaboration with foresters.

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