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Danum Valley Rainforest Research and Training Programme

Lessons for sustainable tropical forestry from Danum hydrological research: Preliminary thoughts

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It is critical that sustainable forestry management within the humid tropics is informed by the latest hydrological research. This includes field and modelling work on hydro-meteorology, hydro-chemistry (Brouwer, 1996), ecohydrology (Martin-Smith, 1998) and hydro-geomorphology (Douglas *et al*. 1995; Chappell *et al*., 2004a) as well as purely water quantity issues. If the basic hydrological description of a region is in error due to a lack of data or models or perhaps misconceived, then less than optimal or even damaging forestry practices may be encouraged (Chappell and Bidin, 2001; Chappell, 2004; Chappell *et al*., 2004bc). Further, it is our belief that behaviour integrated at the catchment-scale (0.1-50 km^2) must be central, to ensure that a distribution of landscape elements (e.g., saturated areas, roads, landslides, canopy gaps etc) are properly represented (Chappell *et al*., 2004b). This noted, there is an increasing awareness of the need to describe forest hydrological processes integrated at even larger scales of 1,000 to 100,000 km^2 to link with simulations of Global Climate Models (Polcher, 1995; Chappell and Fowell, 2003) and forestry policy at the scale of the Forest Management Unit (Abdul Rahim and Zulkifli, 1994).

There are few 0.1-50 km^2 experimental catchments maintained in humid tropical forests. Such catchments in the humid tropics that are informing forestry management include: Babinda in Australia (Bonell *et al*., 1983), and in Malaysia - Bukit Tarek and Jengka in West Malaysia (Abdul Rahim and Zulkifli, 1994; Abdul Rahim *et al*., 1997) and Sipitang (Malmer and Grip, 1990) and Danum in East Malaysia (Douglas *et al*., 1992; Pinard *et al*., 1995; Greer *et al*., 1996). All of these examples examine managed forests (either natural or planted). Research within undisturbed natural forests is of equal value as it provides a reference for local comparisons with the disturbed catchments (so called ‘paired catchment studies’) and serves as a baseline by which to judge Environmental Impact Assessments.

DANUM CATCHMENTS

The Danum catchments are located close to the Danum Valley Field Centre (5^{o}01’ N and 117^{o}48.75’ E), a research and educational station of the Sabah Foundation (Yayasan Sabah) in East Malaysia. Establishment of the research catchments and other hydrometric networks began in 1986 as part of a collaborative agreement between the Sabah Foundation and research-cum-policy sectors of the Malaysian federal and state governments. To aid in the international profile of Danum research, The Royal Society of London were invited to be involved. The two catchments monitored from this beginning were the 1.7 km^2 W8S5 catchment, a undisturbed reference area inside the Danum Valley Conservation Area, and the 0.44 km^2 Baru catchment which was subject to the first episode of commercial selective logging in 1989. Both catchments are covered by natural forest, which is classified as Lowland Dipterocarp forest (Marsh and Greer, 1992). The 721 km^2 Ulu Segama catchment is gauged at the DVFC with water-level records maintained by the Department of Irrigation and Drainage in Malaysia, and ratings and suspended sediment records maintained by the hydrology team at Danum. This team includes permanent field staff and researchers from universities in Malaysia and overseas (notably Universiti Malaysia Sabah, Manchester University, University of Wales Swansea, Lancaster University, and Vrije Universiteit Amsterdam) and the Sabah Foundation itself. Other catchments that have been instrumented for specific projects include the Palum Tambun, the water catchment for DVFC (Sinun *et al.*, 1992), the 4 km^2 Sapat Kalisun catchment (Bidin and Chappell, 2003), and the 1.5 km^2 Jauh and Rafflesia catchments (Douglas and Bidin, 1994). The W8S5 catchment contains four micro-catchments (Bidin, 1995; Sherlock, 1997; Sayer, pers comm), while the Baru catchment contains 14 contributory areas ranging in area from 0.0003 to 0.190 km^2 (Chappell *et al.*, 1999a; 2004a: Figure 1).

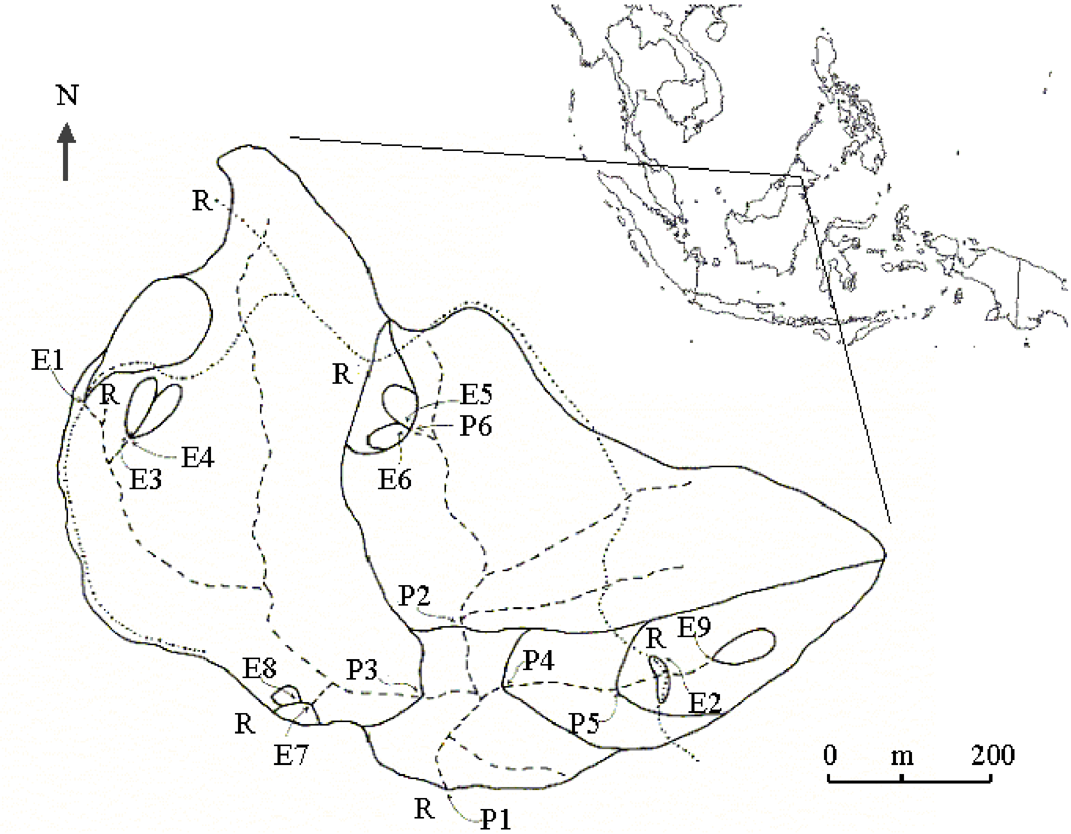

Figure 1. The 0.44 km^2 Baru catchment, near to the Danum Valley Field Centre (5° 01' N and 117° 48.75' E) in Sabah, Malaysian Borneo. The subcatchment divides are shown with a solid line, the streams with a broken line and the haulage roads with a dotted line. The skid trails and highlead locations are not shown.

In addition to the gauging of catchment areas, hillslope plots have been installed for monitoring overland flow (Sinun *et al*., 1992; Douglas *et al*., 1995; Chappell *et al*., 1999, 2004a), soil-water status (Gibbons and Newbery, 2003), and subsurface flow (Sherlock, 1997; Chappell *et al*., 1998, 2004c; Sherlock *et al*., 2000; Chappell and Sherlock, in sub). Canopy plots have been installed for micro-meteorological work (Barker *et al*., 1997; Zipperlen and Press, 1997), wet-canopy evaporation (Sinun *et al*., 1992; Bidin *et al*., 2003) and transpiration (Owen *et al*., 2002). Additionally, distributed measurements of rainfall (Bidin and Chappell, 2003), soil permeability (van der Plas and Bruijnzeel,1993; Chappell et al., 1998), soil erosion and erodibility (Brooks *et al*., 1994; Chappell *et al*., 1999b; Clarke, 2003), soil nutrients (Nussbaum *et al*., 1995; Burghouts *et al*.,1998) and channel sediment characteristics (Fletcher and Muda, 1999; Martin-Smith, 1998) have been undertaken.

FORESTRY IMPLICATIONS FROM HYDRO-METEOROLOGICAL WORK

DVFC receives an annual rainfall of 2,775 mm (± 439 mm; 1986-2002), which is a factor of 2.47 larger than the global mean (Legates and Willmott, 1990). The rainfall exhibits relatively little seasonally (Chappell *et al*., 2001), as expected given its location only 5^{o} north of the Equator. April in all but El Nino years has the least rainfall. In some countries (e.g., Belize), forestry operations are restricted to the dry season in which ground disturbance is likely to be the least. The lack of marked seasonality (as experienced at much larger tropical latitudes in SE Asia, e.g., 15-23^{o}) means that there is no clear dry season in the production forest of the Ulu Segama Forest Reserve surrounding DVFC. The region does, however, also experience cycles in the rainfall due to the El Niño Southern Oscillation (ENSO) phenomena. Recent ENSO-related troughs in the rainfall occurred in 1987 (86% of mean rainfall), 1992 (85%), 1997 (69%), and 1998 (77%). While wetter La Nina periods occurred in 1989 (115% of mean rainfall), 1995 (118%), 1999 (121%) and 2000 (126%). Ideally, major forestry operations such as the cutting of haulage roads should be lessened in these wetter years, though this management option is limited by the poor predictability of the 4-5 year ENSO cycle in the local rainfall (Schneider *et al*., 2003). The observation that there is an exceptionally high spatial variability in seasonal rainfall totals over only a few 100 metres (Bidin and Chappell, 2003) makes it difficult for foresters to collect the reliable rainfall records needed to forecast seasonal and ENSO-related phenomena. As the forest of the Baru catchment was selectively-logged during the La Nina period of 1989, the impact on the soils and hence the stream sediment delivery (Douglas *et al*., 1992) may have been worse than if the operations had coincided with a drier periods (Chappell and Tych, 2002).

The transfer of water to the atmosphere by the processes of wet canopy evaporation and transpiration from tropical trees is shown by most studies in the humid tropics to be greater than that from most shrubs and grasses (Bruijnzeel, 1990, 1996, 2001). Thus, any harvesting of trees is likely to reduce losses to the atmosphere leaving more water available to generate streamflow. While selective harvesting removes less trees in comparison to clearfelling, the resultant increase in streamflow following logging is still observable (Abdul Rahim and Harding, 1992; Chappell *et al*., 2004b), though less than that of clearfelling (Bruijnzeel, 2001). Bidin's work at Danum has added to these findings, by showing that the wet canopy evaporation component of the losses decreases because of the clearing along forest roadways, with losses even increasing in the remaining disturbed forest blocks (Bidin, 2001; Chappell *et al*., 2001; Bidin *et al*., 2003, 2004). This work would suggest that to minimise the reductions in evaporation and hence increase in streamflow may be best achieved by limiting the extent of road-side clearance (‘Matahari’ clearance). To date, work on transpirational losses has only been undertaken at the local scale (Barker *et al*., 1997; Gibbons and Newbery, 2003; Owen *et al*., 2002.), so the effects of forestry on large-scale transpiration is beyond the scope of the Danum studies. We may be able address this question as new research develops at the Global Atmospheric Watch (GAW) tower recently contructed 5 km to the north-east of DVFC by the Malaysian Meteorological Service. There is already much comparative tower work to compare with the proposed GAW studies (Becker, 1996; Davies, 1998; Eschenbach *et al*., 1998; Kumagai *et al*., 2004).

FORESTRY IMPLICATIONS FROM RAINFALL-RUNOFF RESPONSE AND ASSOCIATED SEDIMENT GENERATION

The streams at Danum have a very flashy response in comparison to similarly sized streams in temperate climates. This is shown by the very large ‘quickflow index’ of 50% for the 1.7 km^2 W8S5 catchment (Bidin and Greer, 1997) and the very short DBM-model Time Constant (TC) of 48 minutes for the 0.44 km^2 Baru catchment (Chappell *et al*., 1999a). This is because of the greater rainfall intensities (Bidin, 2001) and because of the relatively impermeable geology. The latter can be shown by comparison of the Baru TC with the 23 day TC of the Bukit Berembun C1 catchment on permeable saprolite (Chappell *et al*., 2004b). The very flashy nature of the rainfall-runoff system at Danum may indicate that relatively little water, flows via deeper (5-10 m) routes towards the streams, with most moving in the upper 1-3 m of soil and weathered rock. The greater waterflow within these upper layers will make the soil/weathered rock more sensitive to disturbance by forestry vehicles and slope cutting for roads. The greater shallow subsurface flow observed is certainly aided by the presence of natural soil pipes within the local Alisol soils (Chappell *et al*., 1999b) close to the DVFC. Several Danum studies (Chappell and Binley, 1992; Bidin, 1995; Sherlock, 1997; Chappell *et al*., 1998; Sayer, pers comm; Chappell and Sherlock, in sub) have highlighted the role of these preferential pathways.

Catchments with flashy river responses often have a high drainage density (Walsh, 1996). At Danum there are few intermittent channels (i.e., those that are seasonally dry) due the relatively limited rainfall seasonality. The density of perennial channels (that carry water all year) and ephemeral channels (that flow only in storms) is, however, very high, approaching 20 km of channel per km^2 of terrain (Walsh and Bidin, 1995). This means that most of the landscape is covered by channels, making it difficult for forestry vehicles to avoid channels (Thang and Chappell, 2004). The work of Chappell *et al.* (2004a) does, however, indicate that it is the perennial channels, and not the more dense ephemeral channels, that generate most of the eroded sediments transported to the downstream. This means that the placement of stream buffer zones (where harvesting and vehicle activity is restricted) on the perennial channels alone, as required for compliance with the Malaysian Criteria and Indicators (MC&I) for sustainable forestry (Thang and Chappell, 2004), should be sufficient protection.

Poor drainage management could, however, result in some local erosion and landslide problems. Within the 0.44 km^2 Baru catchment, two 100 m gully systems have developed as a result of forestry road construction. One gully developed from a roadside drain which over-deepened and then cut across a haulage road, and the other developed on a haulage road where a stream had been inadequately culverted (Chappell *et al*., 1999b). These gullies could have been avoided if a shallower road gradient and more culverting had been used. It should be noted, however, that these two features generated an insignificant proportion of the eroded sediment passing through the main gauging station. Their role in routing greater surface flows to perennials stream channels and hence giving greater peakflows in rivers is possible, but yet to be established with the Danum data. Indeed, the role of the low permeability haulage roads (van der Plas and Bruijnzeel, 1993; Chappell and Ternan, 1997) to the peakflows has also to be established at the catchment-scale with the Danum data.

The dominant source of sediment passing through the main Baru gauging station came from mass movements along the haulage road (Chappell *et al*., 1998, 1999a). Two landslides occurred on the eastern edge of the catchment, and two further just outside the catchment. This would indicate some intrinsic instability in the geological materials within this eastern part of the catchment (Chappell *et al*., 1999b). A secondary factor was, however, the slope cutting for the road construction. Both landslides inside the catchment failed as a result of upslope road drainage which locally percolated through the fill slope, utimately changing the soil stability characteristics (Chappell *et al*., 1999b). The road was constructed in accordance with international forestry policy – keeping roads away from main stream channels (Bruijnzeel, 1992; Dykstra and Heinrich, 1996; Sist *et al*., 1998). The consequence is that the road runs along a bench cut into the slope towards the steeper and hence less stable catchment divides. Our experience is that it is quite diffcult to identify local slope instability in undisturbed areas, and hence avoid them during road alignment operations. Once road materials have failed, then the problem areas can be identified and we would recommend improved drainage systems (e.g., concrete culverts) in these local areas to keep the roads open and sediment from the streams.

Two major collapses of hollow log culverts on very small perennial channels in the north-eastern quadrant of the Baru generated much sediment (Chappell *et al*., 1999b). Hollow log culverts are a cost effective means of directing perennial streams beneath forestry haulage roads within an annual logging coupe. The Baru work may indicate that as a few of them collapse several years after their construction, they may deliver significant volumes of sediment in an extensibly recovering terrain (Douglas *et al*., 1999; Chappell *et al*., 2004a). More work needs to be done to ascertain the longevity of such culverts, particularly where used on primary haulage roads (Forestry Department Peninsular Malaysia, 1999) which need to be kept open for several years.

In conclusion, some of the findings from Danum are giving a unique insight into the interaction between forestry and hydrology. Many aspects of tropical forest hydrology at Danum and elsewhere do, however, remain uncertain, requiring continued research efforts.

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