

WATER PATHWAYS IN HUMID FORESTS: MYTHS vs OBSERVATIONS

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This article is a scientist's perspective on the "popular beliefs" of the hydrological role of humid forests and the aquatic impacts of forestry within the tropical setting of Malaysia and temperate environment of the United Kingdom – two areas at either end of the Eurasian Continent. Over the last 50 years, selective harvesting of natural forests has been the predominant form of forestry in Malaysia, while within the UK over the same period, afforestation with exotic conifers and the subsequent patch clearcutting has dominated. The aim of the analysis of forest and forestry impacts within these two particular regions (somewhat different to Japan) is to provoke debate, rather than to provide a definite statement of well attested conclusions.

A. Introduction

Any land-use has negative and positive impacts, for example urban land-use has pollution and wealth/cultural impacts, respectively. Similarly, managed forests have both positive and negative aspects. For example, in humid tropical regions, the often stated negative social and environmental impacts need to be set against the very positive wealth generation impacts. A major issue for the management of humid forests whether in the UK or Malaysia is the presence of "popular beliefs" about: (a) the hydrological role of forests, and (b) forestry impacts on the water environment. Some popular beliefs are not supported by scientific evidence (i.e., experiments undertaken following the scientific method) or worse still they might be misconceptions of the scientific theory.

What does this mean? From a socio-economic perspective this could mean that development of forest-lands is unnecessarily

restricted, and from an ecological or environmental perspective - policies based on inaccurate science may mean that minor impacts are protected, but significant impacts are worsened by the protective measures for the minor impacts. For example, if one keeps canopy cover over unsurfaced, cut roads, then one might reduce rainsplash erosion, but if the road cannot loose water by solar drying, it may be more likely to fail by mass movement.

So what are these popular beliefs ? Perhaps one can identify at least nine: (i) Riverflow increases during rainstorms because of overland flow on slopes, (ii) Cutting forests increases peakflows by generating more (infiltration-excess) overland flow on slopes, (iii) Forests act like 'sponges' and increase river yield, (iv) Cutting forests reduces riverflows in rainless periods, (v) Rivers become more flashy when forests are cut, (vi) The presence of forests enhances regional rainfall, (vii) Forests improve the biochemical quality of water draining into rivers, (viii) Forests have low rates of erosion and mass movement, and (ix) Cutting forests increases erosion and slope instability.

B. Comparison of popular beliefs with research findings

Each of the nine popular beliefs held within countries such as the UK and Malaysia will be compared against field observations and modelling, predominantly from within the same countries.

1. Riverflow increases during rainstorms because of overland flow on slopes

Scientific field evidence is contrary to this first statement, at least in humid areas such as Malaysia and the UK. There are four sources of evidence for this conclusion.

First, large quantities of surface flow on slopes (outside of channels) is rarely seen. This has been noted since the observations in the 1930's by US foresters such as Charles Hursh. Personal storm-based visual observations in UK, US and Malaysian forests support this observation (e.g., Chappell *et al.*, 1990; 1999). Secondly, plot

studies on dominant slope elements in forests show only a very small proportion of overland flow. For example, at the Danum research areas in equatorial Borneo, overland flow is equivalent to less than 5 percent of streamflow (Sinun *et al.*, 1992; Chappell *et al.*, 1999). A few very localised areas of forest (e.g., stem bases, compacted roads/tracks, log landings, hydrophobic litter on steep slopes) have higher rates than this. For example, unsurfaced skid trails at Danum have some 20 to 50 percent streamflow equivalents (*op cit.*), but it should be remembered that the trail and road surfaces occupy less than 2 percent of the catchment areas (Chappell *et al.*, 2004). Thirdly, rainfall intensities in many humid areas (e.g., upland UK and Malaysia) are much smaller than soil infiltration capacities (i.e., topsoil permeability), particularly under forest (e.g., at Danum compare rainfall intensities in Chappell *et al.*, 2001 with topsoil permeability in Chappell *et al.*, 1998). It might be that forest areas of the world experiencing very intense cyclonic rainfall (e.g., Queensland-Australia, Madagascar, Philippines), soil infiltration capacities are often exceeded (see e.g., Bonell and Gilmour, 1978).

The final source of evidence for a lack of overland flow and hence a dominance of subsurface flow is gained from an examination of chemically conservative tracers in water (e.g., natural chloride), which show much variation in rain and very little variation in river water (e.g., Plynlimon catchments, upland UK: Neal and Kirchner, 2000). Thus rainwater does not travel only over the ground surface of slopes directly to rivers, but mixes with the large subsurface store of water before entering the stream. Thus catchment studies indicate that...

"riverflow increases during rainstorms in humid forests (and grassland areas) largely because of rapid subsurface water movement"

2. Cutting forests increases peakflows by generating more (infiltration-excess) overland flow on slopes

Within humid tropical forests, the most reliable catchment water-balance study related to selective logging effects is possibly that undertaken by the Forest Research Institute of Malaysia (FRIM) at Bukit Berembun in Peninsular Malaysia. Recent re-analysis of these experimental data has shown that the peakflows (here the flows

equalled or exceeded for 10 percent of the time) increased by 1.43 fold directly after harvesting by conventional methods (when highflows in a control catchment reduced slightly: Chappell *et al.* 2004). It is not known whether the temporary increase in the peakflows was due to an increasing proportion of flow from the rapid pathway of overland flow (given that indurated surfaces only covered 4.9 percent of the catchment) or the greater net rainfall that reaches the ground as a result of the reduced wet canopy evaporation. The broadly comparable studies of Subba Rao *et al.* (1985) and Gilmour (1977) indicated much less change.

The author is unaware of any published study on the effect of local patch clearfelling on peakflows in UK forests. In the Pacific Northwest of the USA, analysis by Jones and Grant (1996) indicates a increase in peakflows flowing road construction and harvesting of conifers. Thomas and Megahan (2001) have, however, suggested that these effects may be restricted only to the relatively small storms studied. Thus catchment studies indicate that...

"small increases in river peakflows (for frequent storms) can result from even modest cutting intensities, but there is little conclusive evidence to say that it is due to ground compaction as opposed to the reduced wet canopy evaporation"

3. Forests act like 'sponges' and increase river yield

There are perhaps four key considerations when considering this statement. First, the humid forest canopy itself (or indeed the trunk) has little water storage (Calder, 1990; Tani *et al.*, 2003).

Secondly, soil research as far back as the 1940s in USA (e.g., Hoover, 1949) shows that forest soils tend to have greater porosity than land converted from natural forest to pastoral agriculture. The critical issue for river yield is, however, that there is much more storage of subsurface water below the 1 m of true soil (A & B soil horizons). Drainage from storage in these deeper layers of weathered rock, colluvium or till is now thought to be a very important component of the riverflows generated even from small catchments (see e.g., Hill, 2000; Chappell *et al.*, 2004). The structure of these deeper layers is normally unaffected by forest disturbance.

Thirdly, all experimental catchment studies (certainly from humid lands) show that removal of trees actually increases river yield (Bosch & Hewlett, 1982; Bruijnzeel, 2001a). This is primarily because of the associated reductions in wet canopy evaporation and/or transpiration with tree removal. Conversely, afforestation of moorland catchments in upland UK has reduced river yield, here largely due to the very high rates of wet canopy evaporation (Robinson *et al.*, 2003). This was shown by the seminal work of Mr Frank Law in the 1950s on Bowland Fells near Lancaster (UK), and confirmed by the work of the Institute of Hydrology (now CEH Wallingford) on the Plynlimon catchments, UK. At this site pastureland evaporated 19.6 percent of the incoming precipitation, while the catchment 67.5 percent afforested with conifers evaporated 25.4 percent (Hudson *et al.*, 1997).

Lastly, if natural forest is replaced with water demanding crops (incl. those part of agroforestry programmes) then transpiration could be higher thus reducing riverflow in rainless periods. One example of a water demanding plantation tree that is likely to have an adverse effect on water balance is Eucalyptus (Le Maitre *et al.*, 2002; Robinson *et al.*, 2003). Thus field observations would indicate that...

"small reductions in near-surface porosity (< 1 m) when converting natural forest to agricultural land is insignificant against the storage in the whole river catchment that generates the riverflow. Thus if the 'sponge-effect' means 'storage', then it is likely to be insignificant for river behaviour"

and...

"humid forests may give greater yield than areas with high water demand crops, but certainly less than low demand pastureland"

4. Cutting forests reduces riverflows in rainless periods

Reviews by Bruijnzeel (1990, 1996, 2001a) show that for humid tropical forests, most studies have increased lowflows following forest cutting. Clearly the opposite could be the case if natural forest is replaced by water demanding crops or trees (e.g., Eucalyptus).

The author is unaware of any studies addressing changes in lowflows as a result of conifer afforestation in the UK. Thus field experiments indicate that...

"cutting of forest reserves within humid areas enhances both lowflows and overall river yield due to reduced evapotranspiration, but conversion of natural forest to water demanding crops or trees could have a negative effect on lowflows and yield"

5. Rivers become more flashy when forests are cut

We have recently examined whether stream behaviour becomes more flashy as a result of selective logging of tropical forest. We used two different approaches to re-analyse the datasets for the Bukit Berembun catchments in Peninsular Malaysia (see Abdul Rahim & Harding, 1992). The first method undertaken was the flow-duration curve or FDC (Searcy, 1959) where the flashiness is estimated from the slope of a specified segment of the FDC. Following Ward (1981), the slope between the Q30 (i.e., riverflow equalled or exceeded for 30 percent of the time) and Q70 was chosen. The analysis showed that during the two years of the harvesting and immediate recovery period (1984-5), the conventionally logged catchment became slightly more flashy, but was no different to the pre-logging condition when the longer 1984-8 period was examined. In some contrast, the catchment harvested by Reduced Impact Logging (RIL) actually became less flashy. This probably resulted from an increase in lowflows due to the reduced transpiration when trees were removed (Chappell *et al.*, 2004).

The method of analysing flow-duration-curves is dependent on the particular sections of FDC used to derive the statistics and is, therefore, somewhat subjective. If response characteristics capturing the whole range of behaviour could be derived then the conclusions about change effects would be more reliable. Dynamic models may be able to deliver these, however, one must be aware that such parameter interpretation is only successful with parsimonious modelling approaches (i.e., those with simple and efficient model structures, requiring only few parameters) due to the increasingly acknowledged problem of parameter interaction during the

identification process (Young, 2001). Lancaster's Data-Based-Mechanistic (DBM) modelling is one such parsimonious approach.

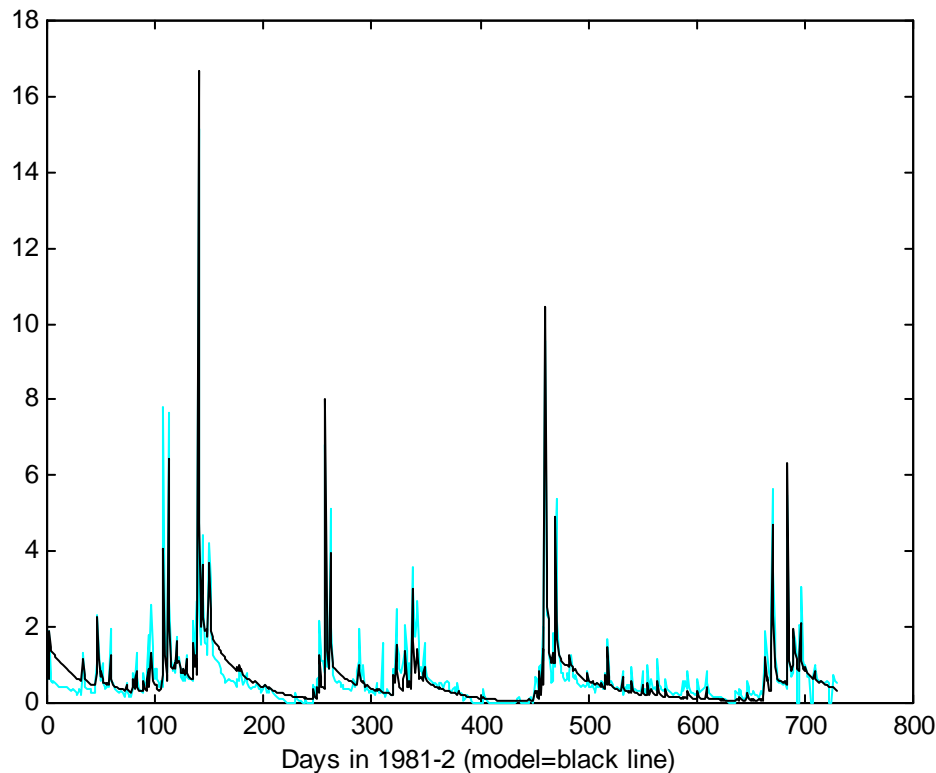


Figure 1 Observed (grey broken line) and simulated (black solid line) riverflow generated by the Bukit Berembun C1 catchment during 1981-2.

DBM combines: (i) model-structure identification based on linear transfer functions (incl. non-linear dynamics), (ii) model-structure rejection using objective statistical inference, and (iii) final model selection by physically-based understanding of system behaviour (Young *et al.*, 1997). The DBM modelling approach was, therefore, applied the Bukit Berembun dataset analysed by the FDC analysis. Two periods were chosen: 1981-2 (prior to logging) and 1984-5 (during and immediate post logging). The non-linearity in the behaviour was captured with the Store-Surrogate Sub-Model (Young, 2001).

The modelling indicated that a simple, first-order model structure could be used to explain almost 90 percent of the riverflow dynamics (Figure 1). Both periods used the same value of the power-law exponent of the non-linear component, so that all of the Dynamics Response Characteristics (DRCs) of the Bukit Berembun behaviour could be described by a single time constant (TC) term.

For the pre-logging period, the TC was 23.06 ± 0.19 days, while during and immediately after logging it was 23.47 ± 0.17 days. Thus this more robust modelling technique indicated the conventional selective logging did not increase the flashiness of the stream behaviour. Clearfell impacts on UK river flashiness have yet to be studied. Thus modelling of the impacts of this very specific type of tropical forestry management system indicates that...

"not all humid forest disturbance makes river behaviour more flashy over a sustained period (e.g., selective logging of equatorial rainforest), however, it is likely that in areas with clearfelling and extensive ground compaction on steep and relatively impermeable terrain – that rivers would become more flashy"

6. The presence of forests enhances regional rainfall

The idea that the presence of forest enhances rainfall has been held by foresters for well over a century (e.g., Brown, 1877). From an observational perspective, the HAPEX-Sahel study has shown that local areas of high evaporation within a semi-arid environment can lead to the local enhancement of rainfall (Taylor & Lebel, 1998). Thus higher rates of evaporation from forest areas could, theoretically, leads to greater rainfall.

For humid tropical regions, there have been several Global Climate Model (GCM) studies of the impact of deforestation. The effects of forest loss on precipitation have, however, been shown to be very variable (Henderson-Sellers *et al.*, 1996; Fowell & Chappell, 2002). This is partly due to the poor performance of current GCMs in describing the spatial and temporal characteristics of tropical rainfall (Fowell & Chappell, 2003).

One area where there is increasing concern over the potential enhancement of precipitation by forests is on high mountains, due to the way cloud forests trap cloud water (Bruinjeel, 2001b). Thus field experiments and GCM modelling results indicate...

"while there is a mechanism for the enhancement of precipitation by forests, strong observational evidence is still lacking"

7. Forests improve the biochemical quality of water draining into rivers

From the 1930s to 1960s UK foresters planted conifers around upland reservoirs to protect water supplies from agricultural pollution (what were described as a "cordon sanitaire"). I should like to raise four issues related to whether humid forests improve the biochemical quality of water draining to rivers. First, forests compared to other land-uses normally have low chemical inputs, and so tend to have less nutrient-, pesticide-, and industrial-pollution losses to water courses. Secondly, as riverside trees can extract nutrients from shallow subsurface waters then if subsurface flow near to a stream is shallow and not bypassing the root-zone (via drains, channels, soil pipes or deep pathways) then trees should "buffer" streams from pollution from upslope agricultural activities (Quinn *et al.* 2001; Prosser *et al.* 1999). Thirdly, conifers planted on acidic geologies can exacerbate the acidification of streams in humid temperate uplands (e.g., Chappell *et al.*, 1990, 1996; Waters and Jenkins, 1992). Lastly, forest disturbance (e.g., harvesting) has been shown to increase losses of nutrients within a wide global range of humid areas (Swank, 1988; Bruijnzeel, 1990; Stevens *et al.*, 1995). While this conclusion is well attested, there are very few studies quantifying the magnitude and duration of this impact for selective tropical forestry (Chappell *et al.*, 2004). The most reliable catchment study is probably that undertaken at Bukit Berembun in Peninsular Malaysia by Yusop (1989). At this site, the flux of macro-nutrients (nitrate, phosphate, potassium, calcium & magnesium) increased by 1.7 to 5.6 fold in the selectively logged (by conventional methods) catchment and 1.2 to 2.1 fold in the RIL catchment during the harvesting year. During the harvesting year nitrate losses increased the most, but most critically returned to near natural levels within 6-months of cessation of harvesting within this tropical environment. Such rapid recovery in nutrient cycling is even observed when tropical forest is clearfelled and burnt (Malmer & Grip, 1994). With clearfelling of UK conifer forests, harvesting impacts on nutrients were shown to persist for longer – eight years in the case of the Hore catchment on Plynlimon (Neal *et al.*, 1997). Thus field experiments indicate...

"the presence of humid woods and forests is beneficial to the biochemical quality of streams, except where acid moorlands are afforested with conifers"

and...

" harvesting of humid forests enhances nutrient losses to streams but the duration of the impact (months or years) depends on the primary productivity of the system"

8. Forests have low rates of erosion and mass movement

Observation of sediment budgets for forests (natural and planted) shows that forests can have high or low rates of erosion. For example, local areas of conifer plantations in upland UK undergoing clearfelling can have an erosion rate as low as 57.1 t/km²/yr (Hore catchment, Plynlimon: Kirby *et al.* 1991), while an undisturbed rainforest catchment on a mudstone in Borneo can have an erosion rate as high as 300 t/km²/yr (W8S5 catchment, Borneo: Chappell *et al.*, 2004). Thus field experiments indicate...

"in comparison to other vegetated area some forest-lands have high rates of erosion, others have low (due to differences in geology-tectonics-relief or climate). Clearly, the presence of a permanent vegetation cover helps to protect against erosion"

9. Cutting forests increases erosion and slope instability

All studies show that forest drainage, road construction and harvesting increases erosion and/or slope instability. For example, in upland UK, Kirby *et al.* (1991) showed over a period when improved pasture had a sediment yield of 6.1 t/km²/yr (Cyff catchment), that three adjacent catchments with artificially drained conifer plantations (Tanllwyth, Hore and Hafren catchments) had a yield of 12.1, 24.4, and 35.3 t/km²/yr or a 1.9 to 5.8 fold larger. With local clearfelling, the Hore catchment sediment yield then increased to 57.1 t/km²/yr or a 2.3 fold increase above the drained levels. It

should be noted that this rate is no larger than the average sediment yield of 50 t/km²/yr for small UK catchments (Moffat, 1991).

In the humid tropics the magnitude of the impact of forestry disturbance on sediment yield is generally large, but highly variable. Our focus has been with selective forestry impacts. Chappell *et al.* (2004) suggests that there are only four studies assessing the impact of selective logging on natural forest in the tropics and that all of these were undertaken in Malaysia. Two of these studies showed 4.3 and 5.3 fold increases in sediment yield following forestry road construction and harvesting on mudstones, while the other two in granite areas have 20-56 fold increases. Given the lack of studies it becomes very difficult to accurately identify: (a) the most sensitive areas of tropical regions, and (b) erosional differences between different forestry practices. Thus field experiments and modelling indicates...

"forestry operations in some areas of the humid tropics have a large negative impact on erosion and slope instability, but much more research is required to better identify protection areas and best practices"

C. Conclusions

The chemical quality of rivers in humid natural forests is generally better than that within areas of agriculture and industry. Many negative impacts popularly believed to result from forestry operations in humid regions, such as a reduction of lowflows and water resources, changes in catchment storage capacity and rainfall enhancement, are not clearly evident in experimental results. Changes in river flashiness may not be marked with some forestry systems in some areas, e.g., selective logging of Malaysian rain forests.

In some contrast, disturbance of humid forests does, however, significantly increase river turbidity. Some of the largest absolute changes in turbidity occur with forest disturbance in the humid tropics and considerably more research to identify those forestry practices which have the least impact are needed. One suggestion for

debate would be to focus environmental protection measures only on those impacts: (a) where there is robust scientific evidence for a change having taken place, and (b) where that absolute or relative change is very large. Erosional and mass movement impacts fall within this category.

The forest industry is important socially, economically and environmentally, and all of these aspects need to be balanced.

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