(DE)FORESTATION AND DRY SEASON FLOW IN THE TROPICS: A CLOSER LOOK

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BRUIJNZEEL, L.A. 1989. (De)Forestation and dry season flow in the tropics: a closer look. (1) The effect of clearing or reforesting land in the humid tropics on dry season flow is examined by comparing results from scientific experiments with "real world" examples; (2) The apparently conflicting evidence can be resolved by taking into account the net effect of changes in infiltration opportunities and evapotranspiration (ET) associated with the respective land use types : if infiltration opportunities after conversion decrease to the extent that the increase in volumes of stormflow exceed the increase in baseflow associated with reduced ET, then dry season flow will decrease and vice versa; (3) The effect of reforesting strongly eroded soils will not only reflect the balance between changes in infiltration and ET, but will also depend on the available water storage capacity of the soil. Further work is needed on this aspect of the relation between infiltration and ET; (4) Increases in stormflow volumes are fairly small for a well-planned conversion operation, but any benefits of increased dry season water yield are more than offset by increased stream sedimentation rates; (5) Site-specific (regional) guidelines for land clearing operations are urgently needed; presently available guidelines should be given wider application.

Key words: Tropical forest hydrology - deforestation - forestation - dry season flow - environmental management

Introduction

It is now well established that following clearance of tropical forest land and conversion to other types of land use, there is an initial increase in **total** (annual) streamflow (Bruijnzeel 1986, 1987, Abdul Rahim 1988). This increase may be permanent when converting tall forest to grassland or shallow rooted agricultural crops, or temporary in the case of a conversion to tree plantations (Bruijnzeel 1986).

Similarly, there is little doubt that in general an undisturbed forest cover moderates peakflow rates and stormflow volumes, although the influence on the magnitude of extreme events is marginal at best (Gilmour 1977a, Hewlett 1982).

The evidence with respect to the effect of (de)forestation on **dry-season** flow rates, however, seems contradictory. On the one hand, reports of greatly diminished flows abound (Van Dijk & Vogelzang 1948, Daniel & Kulasingam 1974, Hardjono 1980, RIN 1985, Nooteboom 1987), but significant increases have been observed as well (Gilmour 1977a, Edwards 1979a, Abdul Rahim 1987). In fact, in a country like Indonesia the issue is as hot as it was some sixty years ago, when lively discussion of the subject took place (summarised by Van Es 1934).

Here, I seek to clarify the situation by carefully interpreting a number of quantitative studies representing contrasting climatic and pedological situations, rather than bringing in a great deal of qualitative information. It will be shown that the two viewpoints are not contradictory, when one takes into account the prevailing climatic, pedological and hydrological setting of an area, as well as the way in which conversions and subsequent land use practices were carried out.

Some methodological comments

For a proper understanding of research results, insight in the limitations of the measurement techniques employed is a prerequisite. Simply comparing streamflow figures for catchment areas with contrasting land use types may lead to wrong conclusions because of the possibility of catchment leakage (Hewlett & Fortson 1983). This holds especially for small headwater catchments, where streams are often not incised through the entire weathering mantle, although large streams may also lose water to their floodplains. For example, Richardson (1982) found streamflow totals for small catchments covered with montane rain forest and mature plantations of *Pinus caribaea* in Jamaica to differ by about 150 *mm* y^1. However, the corresponding values for forest evapotranspiration (ET) were considerably in excess (by at least 600 *mm*) of what has been reported for similar forests elsewhere (Bruijnzeel 1988, 1989), suggesting serious leakage. Likewise, streamflow from a mature *Eucalyptus robusta* plantation in Madagascar was reported to be some 200 *mm* y^1 below that for nearby natural forest (Bailly *et al.* 1974, wet years only). Since the eucalypt covered catchment was considerably smaller than the rain forested one, and since small catchments in the area showed consistently lower streamflow totals than larger ones with the same vegetation (Bailly *et al.* 1974), it remains to be seen to what extent the quoted difference reflects a real vegetation effect or merely a difference in leakage.

Another complicating factor in the evaluation of the hydrological effects of cover transformations is the year to year variability of weather. In addition, areal precipitation estimates for larger tropical basins, especially forested ones where gauge densities are usually low, are frequently unreliable due to the large spatial variability of rainfall (Aitken *et al.* 1972). Dyhr-Nielsen (1986), for example, was unable to detect any systematic changes in streamflow patterns in northeast Thailand, despite extensive deforestation in the area over the last 30-40 years. Qian (1983) arrived at the same conclusion after analysing streamflow and rainfall records for the island of Hainan, southern China, over the 1960s and 1970s, during which period large scale deforestation occurred.

An effective way to overcome most of these problems is the so-called **"paired catchment method"** (Hewlett & Fortson 1983). Basically the technique involves the hydrological comparison of (at least) two catchments of similar size, geology and vegetation: a "control" (to be left unchanged), and an "experimental" or "treatment" basin. The comparison is made during an initial calibration phase (which may take several years, depending on local rainfall variability) and during a subsequent treatment period. The degree to which linear regression equations linking the streamflows of the two catchments, as derived during the calibration period, change after the treatment is a measure of the effect of the latter (Figure 1a). The total duration of such an experiment may easily span a decade (calibration, clearing, planting, maturation of the new vegetation).

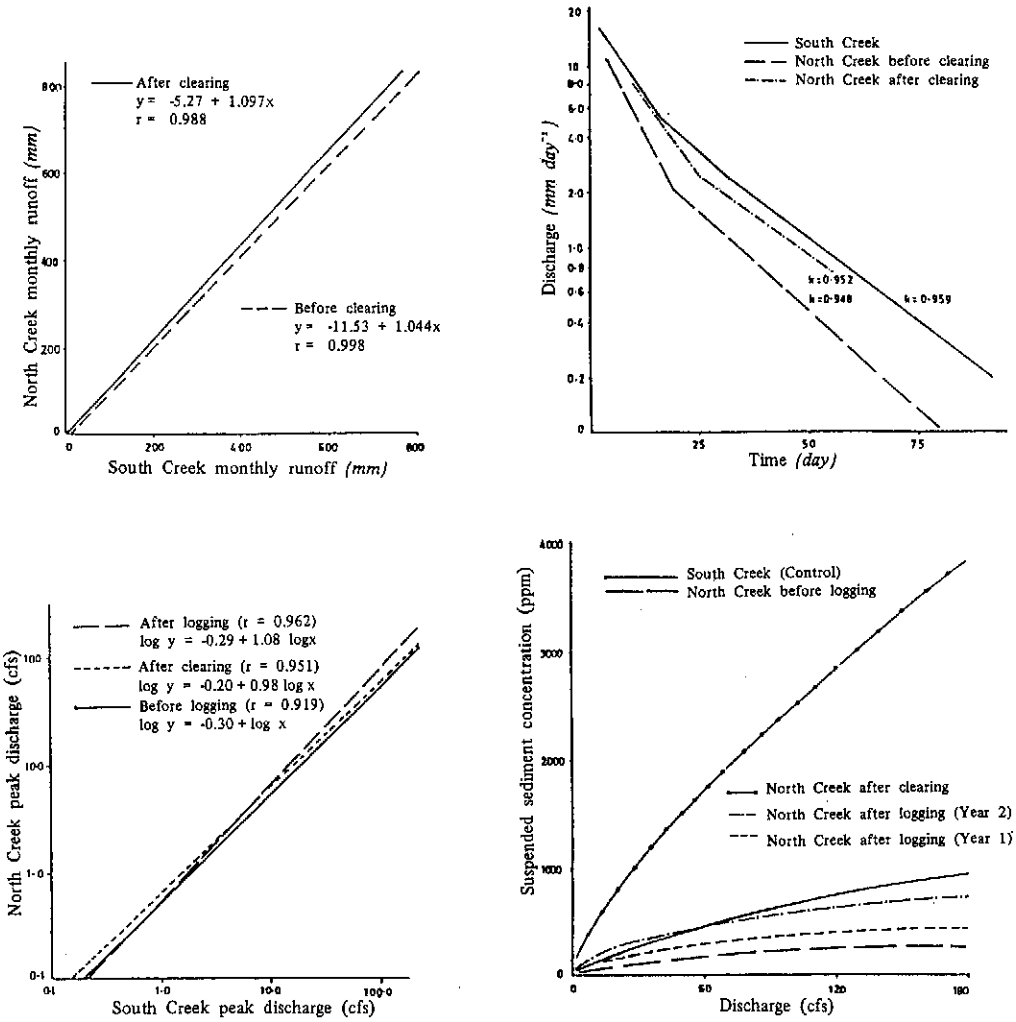

Figure 1. Monthly runoff (a), baseflow recession curves (b), peak discharge (c), and suspended sediment concentrations (d) at Babinda, Queensland, before and after forest clearing (after Gilmour 1977b)

In the following, a number of paired catchment and other studies conducted in the tropics will be described briefly. Their results will be used to illustrate the various possible alterations in streamflow patterns after (de)forestation as influenced by differences in rainfall regime and intensity, soil characteristics *et cetera.*

Tropical forest and dry-season flow: Results of selected studies

Babinda, Queensland

In 1969 the Queensland Forestry Department established an experiment near Babinda to study the effects of logging and clearing rain forest areas and converting them to grassland. The area receives more than 4000 *mm* of rain per year, about half of this occurring during a condensed rainy season of three months (January through March). The monthly streamflow pattern reflects the strong seasonality of the rainfall, with about 60% of the annual flow occurring during the months of February, March and April (Gilmour 1977a). Although soils are deep, the vertical permeability of the soil decreases dramatically from a depth of 10 *cm* onwards (Bonell & Gilmour 1978). This, together with the extremely high rainfall intensities recorded in the area (Gilmour & Bonell 1979), produces widespread so-called **"saturation overland flow"** (the process in which additions of rainfall infiltrating into the topsoil cannot be fully accommodated by the subsoil, thereby forcing water levels in the soil to rise to the surface, after which any new rain flows along the surface as overland flow), also under forested conditions (Bonell & Gilmour 1978). This type of runoff is able to attain considerable velocities while moving over a hillslope and reaches the stream in time to contribute directly to stormflow. The volume of stormflow at Babinda reaches the astonishingly high figure of 47% of total streamflow (Gilmour 1977a), reflecting the extreme importance of overland flow in this particular case (compare the 5 - 7% reported by Bruijnzeel (1983) for a similar-sized forested catchment in central Java underlain by deep deposits of volcanic tuffs and experiencing virtually no overland flow).

Both catchments at Babinda were covered by rain forest prior to the experiment. After a calibration period of 18 months, one catchment (North Creek, 18.3 *ha*) was logged in June 1971 and 2/3 of the area was cleared in July 1973, whereas the control catchment (South Creek, 25.7 *ha*) remained unaltered. The planned conversion to pasture land did not materialise, however, and the cleared catchment was gradually recolonised by grasses and shrubs. Gilmour (1977a) summarised the results with respect to streamflow regime for the first six years of the experiment as follows (Figure 1):

- There were no significant differences in monthly streamflows before and after logging, but a significant ($p = 0.05$) increase of 10% occurred in the two years after clearing (Figure 1a);
- There was a highly significant ($p = 0.001$) rise in minimum weekly discharge after clearing (none after logging) (Figure 1b; note the difference in baseflow recession rates between catchments before the treatment, reflecting slight differences in soil water storage capacity, slopes, *etc.*);

- Peak discharges increased slightly following logging and clearing; the statistical evidence for this is weak, however, as increases following logging mainly occurred at the top end of the range, whilst after clearing the effect was particularly evident at the lower end (Figure 1c);
- Suspended sediment concentrations increased two- to three-fold following logging, but rose dramatically after clearing (Figure 1d).

Gilmour (1977a) concluded that in the context of this experiment, logging caused virtually no detectable changes in streamflow regime, a fact he ascribed to the rather extensive character of the type of logging practised, which leaves a fair amount of canopy (and presumably the forest floor as well) intact. Also, stormflows at Babinda seem to be determined primarily by the rather extreme combination of rainfall and soil characteristics rather than by differences in land use, even after clearing. However, although dry season flow rates were positively affected by the clearing, the tenfold increase in suspended sediment loads after clearing is a cause for concern and far outweighs the possible benefits of increased dry season flow.

Fritsch (1983) reached similar conclusions through a paired catchment study involving mechanical clearing of rain forest in French Guyana. Again, rainfall and hillslope hydrological patterns were such that runoff coefficients, even under forested conditions, were already close to what seems **"physically possible"** (Fritsch 1983).

Sungai Tekam, Peninsular Malaysia

Several Malaysian agencies set up a major study to quantify the effects of converting lowland dipterocarp forest to oil palm plantations in Pahang, Peninsular Malaysia (Abdul Rahim 1987). Although the study was initiated in 1973 the actual calibration period started in 1977, followed by a **"transition period"** of felling, burning and planting between 1980 and 1983. Results for the first six years were reported by DID (1982, 1986; summarised by Abdul Rahim 1987). During this period the area received on average some 1730 *mm* of rain per year, about 200 *mm* below average. Average annual streamflow from the forest amounted to about 230 *mm* (DID 1986). The gently sloping area is underlain by lateritic shales (control basin, 56 *ha*) and andesitic rocks (treatment basin, 153 *ha*), in which deep oxisols have developed The treatment was carried out in two phases: the lower 97 *ha* (63%; catchment B) of the experimental basin was logged in July 1980 (burning completed in April 1981), the rest (catchment A) by the end of 1982, with burning completed in June 1983. Although the operation can be considered to be representative of current land clearing procedures, the gradual clearance makes the evaluation of any hydrological effects less straighforward. Another complicating factor is the fact that shortly after the establishment of a network of agricultural roads in the treated area (summer 1981), the main stream channel was cleared of logs, which again produced a distinct change in the catchment's response to rainfall (Figure 2b).

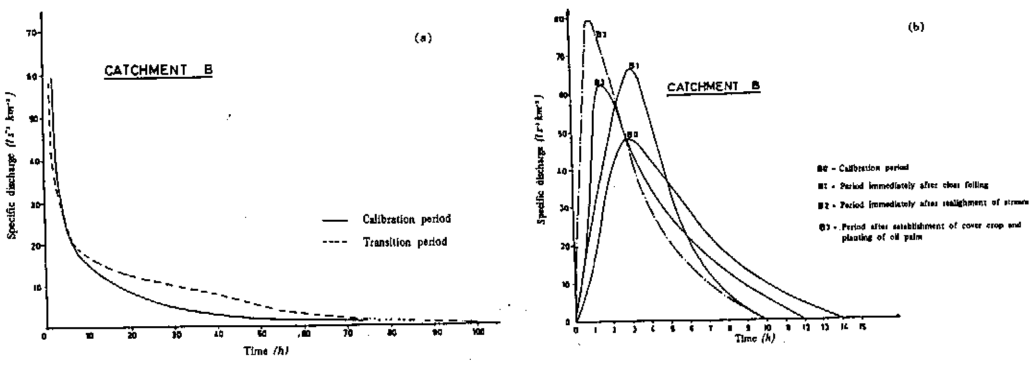

Figure 2. Flow duration curves (a) and 1-*h* unit hydrographs (b) for catchment B at Sungai Tekam, Peninsular Malaysia, before and after forest clearing (after DID 1986)

The following conclusions were drawn with regards to the effects on streamflow regime of the partial (63%) conversion of forest to oil palm plantations (DID 1986, Abdul Rahim 1987):

- The greatest change in streamflow was (again) associated with an increase in the baseflow component (Figure 2a): the relative contribution of baseflow to total streamflow increased from 66.9% during the calibration to 86.1% during the first two years of the treatment;
- Variations in stormflow volumes were such that no significant change was observed following clearing; however, peak specific discharges increased and time to peak decreased considerably, notably after the re-alignment of the stream; the effect was softened slightly after establishment of the cover crop, although by that time the upper part of the catchment had been cleared as well (Figure 2b);
- Suspended sediment loads of the partially deforested basin rose from a mere 0.3 *t* ha^{1} y^{1} during calibration to 4.1 *t* ha^{1} y^{1} (a 14-fold increase) during the initial clearing, followed by a decrease after establishment of the cover crop to 1.6 *t* ha^{1} y^{1}, still five times higher than the original rate; corresponding increases for the actually cleared area were even higher: nineteen, seven and four times during the first, second and third year after the conversion respectively.

The relative absence of increased stormflows at Sungai Tekam already indicates that massive overland flow along the hillsides does not occur, although the clearing operation resulted locally in strong reductions of topsoil infiltration capacity (DID 1986). Any increases as observed will mostly be due to the increased area occupied by roads and similar compacted areas (Swindel *et al.* 1983), and to a lesser extent to higher soil moisture levels associated with reduced ET (Hsia 1987). The latter is mainly reflected in the significantly higher baseflow totals observed during the transition period. The assertion of Daniel & Kulasingam (1974) that baseflows will be halved following this type of forest conversion is not supported by the present data. However, as in the

Queensland and Guyanan examples, the increased transport of sediment by the streams after the conversion seems to be the dominant feature (Abdul Rahim 1987).

Mbeya, Tanzania

In 1958, a study was initiated at Mbeya, southern Tanzania, by EAAFRO and several departments of the then Tanganyika Government to study the effects of forest clearance and indigenous agricultural practices on streamflow and erosion (Blackie & Edwards 1979). Mean annual rainfall is 1800 *mm* and falls entirely between December and April. Rainfall intensities in this elevated (2500 *m*) region are relatively low, which in combination with the highly permeable nature of the volcanic soils results in relatively low erosion rates (Edwards 1979a). The soils are generally at least 1 *m* deep and overlie a gneissic basement. The control catchment (16.3 *ha*) was covered with dense evergreen montane forest (2/3), with annual grasses and shrubs occupying the upper one-third. The cultivated catchment (20.2 *ha*) had 50% of its surface cultivated with no soil conservation measures other than the placing of "bunds" of maize stalks approximately along the contours. The other half was under annual grasses, grazed by goats and sheep (Edwards 1979a).

Figure 3 shows the mean rainfall and streamflow patterns for the two basins for the period 1958 - 1968, from which the following conclusions may be drawn:

- Total water yield from the forested area remained (again) significantly below that from the agricultural one (28 *vs.* 40% of rainfall);
- Seasonal flow patterns for these catchments with their deep permeable soils were such that monthly streamflow totals leaving the agricultural basin were higher throughout the year, that is, also during the dry season, despite a lower (by 14%) rainfall input for the agricultural area.

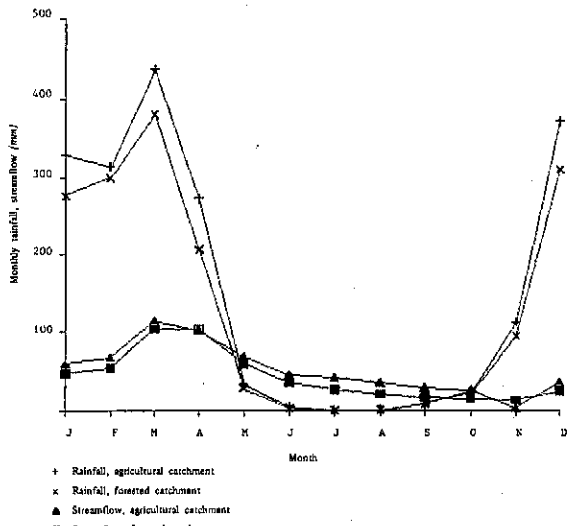

Figure 3. Monthly rainfall and streamflow for a forested and an agricultural catchment at Mbeya, Tanzania (based on data presented by Edwards 1979a)

Since overland flow is absent from these catchments and stormflows make up only a minor fraction of the total flow, it follows that the observed differences in streamflow reflect differences in ET associated with the two vegetation types. This was confirmed by separate measurements of soil moisture depletion (Edwards 1979a).

The overall conclusion from the Mbeya experiment must be that, as long as top-soil infiltration capacities remain adequate (either naturally or through soil conservation practices), dry season flows from cultivated areas on soils of sufficient depth will be higher than from forested areas.

The suspended sediment load of the stream draining the agricultural catchment amounted to 5.6 $t\ ha^{-1}\ y^{-1}$, whereas the few data available for the forested area suggested values below 2 $t\ ha^{-1}\ y^{-1}$ (Edwards 1979b).

Pidekso, central Java

A situation which differs in many ways from the case studies described above may be found in the seriously degraded uplands of Java. Within the framework of the FAO/UNDP Upper Solo Watershed Management Project a number of catchments were instrumented in the mid-seventies to monitor streamflow and suspended sediment load. Results over the year 1978 for the 354-*ha* Gluguk catchment (entirely reforested in 1967 with pines, teak and mahogany), and the adjacent 207-*ha* Kiteran catchment (fully under dryland agricultural use), were presented (Hardjono 1980). Although not of the paired catchment type (no calibration period or statistical treatment of data), and therefore subject to unspecified differences in catchment leakage, this study is the only one I know of that documents the hydrological effects of reafforestation of degraded agricultural uplands in the humid tropics. In addition, it comes closer to the real world situation than most of the studies quoted above.

The area experiences a seasonal rainfall pattern with an average of four months with less than 60 *mm* and an annual total of about 2500 *mm*. Rainfall intensities are high and soil erosion in the region severe (Dames 1955). Soils of the catchments are infertile, often shallow and of the "andesitic lateritic" type (Dames 1955).

The flow regimes of the two streams (Figure 4) reveal several interesting points:

- Although total water yield of the reforested catchment was decidedly lower than that of its agricultural neighbour at 45% of incident rainfall versus 65% respectively (Hardjono 1980), the four-month long dry season did not eliminate streamflow from the forested area, whereas it did after two months in the degraded agricultural area (Figure 4a);
- Total dry season flow from the forest amounted to almost 5 *mm*, and to only 1.6 *mm* from the agricultural catchment;
- Monthly streamflow totals during the wet season were invariably higher for the agricultural catchment, presumably because of decreased topsoil infiltration opportunities (increased surface runoff) and/or lower rates of water consumption by the crops as compared to the forest;

- Monthly streamflow totals in both catchments dropped extremely rapidly during periods of low rainfall (*e.g.* May), an indication of the very low storage capacities of these eroded soils; when the rains returned after a dry period (*e.g.* June, November, December), streamflow levels in the forest area remained low, not only in comparison to the agricultural catchment, but also in comparison to flows observed during mon ths of similar rainfall during the wet season (*e.g.* December *vs.* April); this suggests severe depletion of soil moisture reserves by the trees during the dry season.

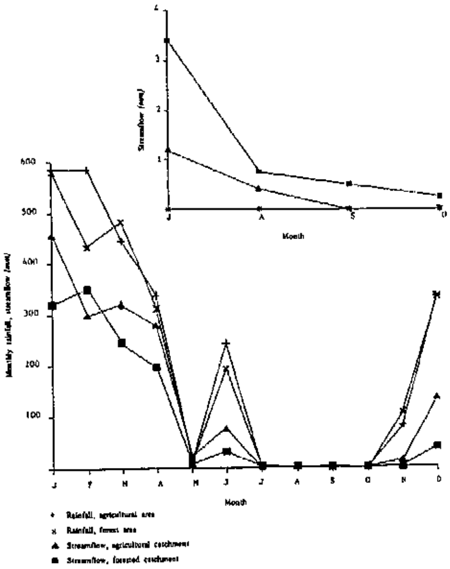

Figure 4. Monthly rainfall and streamflow for a forested and an agricultural catchment at Pidekso, central Java (based on data presented by Hardjono 1980)

Accepting the figures presented by Hardjono (1980) at face value, they could be taken as evidence that reafforestation of degraded lands restores dry season flows (Figure 4a). This would imply that the higher ET of the forest would be more than compensated for by the increased infiltration opportunities induced by reafforestation. However, accepting this hypothesis, it is difficult to envisage how the total annual water yield from the forest can be so much lower (580 *mm* after correcting for differences in rainfall) than that from the agricultural catchment. Therefore, also in view of the limited moisture storage capacity of the soils and the severe depletion of moisture reserves at the end of the dry season in the forest soil, it is much more likely that the higher "summer" baseflows recorded for the forested catchment reflect a larger (+ 71%) catchment area (*i.e.* less leakage) rather than anything else. Clearly, further work using a more stringent approach is needed to arrive at firm conclusions with respect to the hydrological effects of reafforesting shallow degraded soils. Unfortunately both catchments were inundated in the early eighties following the establishment of a major reservoir in the area (S. Wangsadidjaja, personal communication).

Suspended sediment loads for the two catchments amounted to 8.1 (forest) and 20.2 (agriculture) $t\ ha^{-1}\ y^{-1}$ (Hardjono 1980).

Konto area, east Java

The Kali Konto in east Java is one of the few medium sized tropical rivers (catchment area 233 km^2) for which relatively reliable streamflow data are available for an extended period. A comparison of pre-war records, when the basin was largely forested, with data for the period 1951-1972, by which time a fair proportion of forest land had been converted to shrubland, dryland agriculture and build-up areas (RIN 1985), is shown in Figure 5.

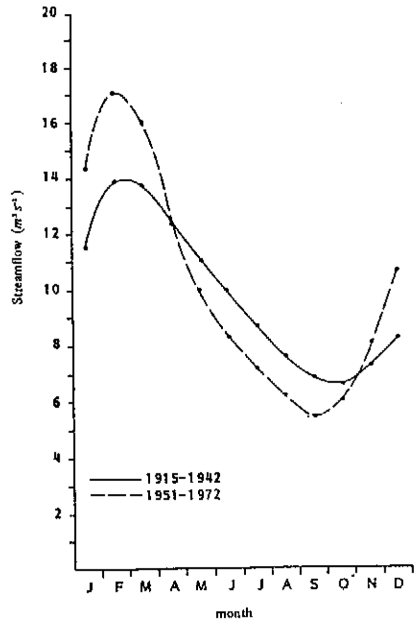

Figure 5. Change in streamflow regime with time for the Konto river, east Java (after RIN 1985)

The higher flows observed during the rainy season (November-March) of the second period reflect the decreased infiltration opportunities associated with the increased area occupied by impervious surfaces, such as roads, yards, roofs, *et cetera* rather than increased surface runoff from agricultural land (Bruijnzeel 1986, Schomaker 1988). The water thus lost as direct runoff cannot contribute to deep percolation, causing the diminished flow rates observed during the dry season (Figure 5).

Support for these ideas comes from a comparison of reservoir siltation rates and recent erosion trials in the area: according to Brabben (1978) the Konto annually discharges some 590,000 m^3 of sediment into the Selorejo reservoir (*ca.* 30 $t\ ha^{-1}\ y^{-1}$), whereas surface erosion rates from agricultural land and build-up areas were shown to be in the order of 5 - 25 and about 150 $t\ ha^{-1}\ y^{-1}$ respectively (Schomaker 1988).

Discussion

Having examined various streamflow patterns associated with forested or non-forested conditions for different combinations of rainfall and soil characteristics in some detail, we will now try and reconcile the apparently conflicting evidence.

It would seem as though the surface infiltration capacity (seen in relation to prevailing rainfall intensities) and ET associated with the respective types of land use play a key role in determining what happens to the flow regime after conversion (Bruijnzeel 1986). Thus, if infiltration opportunities after forest removal decrease to the extent that the amount of water leaving an area immediately as stormflow exceeds the gain in baseflow associated with decreased ET, then diminished dry season flow is the result (Figure 5). Reduced infiltration may either result from an increase in the area occupied by impervious surfaces (roads, landings, villages: Ruslan & Manan 1980, Schomaker 1988), the use of heavy machinery during forest harvesting or subsequent agriculture (Dias & Nortcliff 1985a, b), overgrazing (Dunne 1989) or other improper agricultural practices (Lal 1983). This situation, of course, is found all over the tropics and can generally be held responsible for the deterioration of streamflow regimes so commonly observed (Nooteboom 1987).

If, on the other hand, surface infiltration characteristics are maintained, either because of a fortunate combination of stable soil aggregates and low rainfall erosivity such as at Mbeya, or by deliberate soil conservation practices (Roose 1977, Mensah-Bonsu & Obeng 1979), then the effect of reduced ET after clearing will show up as increased baseflow (Figure 3). The effect becomes more prominent as the length of the dry season increases (Figures 1, 3), reflecting differences in rooting depth between forests and agricultural crops/ grassland (Gilmour 1977a, Edwards 1979a).

The Tanzanian example, however, must be regarded as exceptional. Generally, a certain amount of soil disturbance and permanently increased impervious surface area cannot be avoided upon forest conversion. However, studies like that at Sungai Tekam and many others (Bosch & Hewlett 1982, Hewlett 1982) have shown that the effect associated with reduced ET overrides that of reduced infiltration as long as a reasonable amount of care (road layout, *etc.*) is practised during the operation. In other words, although stormflow volumes will be increased to some extent after forest removal (Figure 2b), this loss of water is not large enough to cause a reduction in baseflow levels. On the contrary, these will be higher than before (Figures 1b, 2a).

Although the above considerations enable one to understand why the reforestation of tropical grasslands in certain cases (*e.g.* Kammer & Raj 1979, Samraj *et al.* 1988) resulted in considerably reduced dry season flows, it would be preliminary to expect that reforesting heavily eroding lands invariably leads to improved dry season flows (*cf.* Figure 4). Such an improvement will not only be determined by the net outcome of changes in ET and infiltration opportunities, but also by the actual moisture storage capacity of the soil

(Bruijnzeel 1987), which may be strongly reduced in case of severely eroded soils. It is unfortunate that the only study dealing with the hydrological effects of reforesting eroding uplands in the humid tropics (Hardjono 1980) is not very stringent. The results could be taken to indicate that soil water storage capacities in this case were such that the increase in ET was just about compensated by the improved infiltration characteristics of the reforested area (Figure 4a). However, based on the respective recession characteristics of the two streams (Figure 4), it could equally well be argued that Hardjono's data reflect a difference in catchment leakage rather than anything else.

As such further work is needed to clarify the situation with respect to the influence of reforestation of degraded areas on dry season flows. Such studies should be of the paired catchment type, preferably supplemented by micro-meteorological and physiological investigations that would permit modelling of the processes involved. This in turn would facilitate extrapolations of the results to other areas (*cf.* Shuttleworth 1988).

Although the examples given above suggest that stormflows can be kept within reasonable limits by properly planning a forest conversion, the observed increases in amounts of sediment transported by the streams after the event were a cause for concern in virtually all cases (*cf.* Figure 1d). The observations of Hardjono (1980) are particularly relevant in this regard: eleven years after reforesting a seriously degraded area the annual suspended sediment load still amounted to 8 $t\ ha^{1}\ y^{1}$ *vs.* 20 $t\ ha^{1}\ y^{1}$ before reforestation). Therefore, even though surface erosion in the reforested basin will have become minimal (Wiersum 1985), there is still a considerable amount of sediment in the river system and it may take years, if not decades (Pearce 1986), for sediment loads to approach the levels present before degradation (in this case *ca.* 3 $t\ ha^{1}\ y^{1}$: Bruijnzeel 1983).

Guidelines to minimise adverse effects of forest cover transformations are available (Cameron & Henderson 1979, Pearce & Hamilton 1986). Although site conditions will differ between regions, comprehensive planning of equipment to be used, layout and drainage of roads, landings and stream crossings as well as maintaining a riparian buffer zone, are all essential in minimising stream sedimentation, especially when used in combination. Application of these guidelines was shown to produce a considerable reduction in streamwater sediment concentrations in Queensland (Gilmour 1977b). Since roads generally produce far more sediment than any other part of a harvested forest (Gilmour 1977b, O'Loughlin *et al.* 1980), their proper positioning and drainage is of paramount importance and indeed more effective in reducing stream sediment concentrations than a buffer zone *per se* (O'Loughlin *et al.* 1980).

Until the application of such guidelines becomes standard practice in the humid tropics, any possible benefits of increased dry season flows following forest clearing will be more than offset by the concurrent deterioration of water quality.

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