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Tropical forest hydrology and the role of the UNESCO International Hydrological Programme*

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Abstract

The paper outlines a perspective on tropical forest hydrology within the context of an international hydrological programme. Experience in tropical forest hydrology research in North East Australia is a focal point for comparision with international activities elsewhere. The impacts of climate variability and change are considered briefly, as well as those of reforestation of degraded land on the land use hydrology, which requires a longer term vision and support of long term experimental catchments. Sadley, too few long term experimental catchments have been maintained in the humid tropicsand there have been some significant closures even of these sites in recent years. Yet the case for long-term experiments is strengthened by the problematic issue of separating anthropogenic influences (such as land use change) on the hydrology of landscapes from the effects of climate variability at a time of escalation in population and related socio-economic pressures in the humid tropics. Particular emphasis is made of the need for greater consideration for the social and cultural dimensions of forest management within forest hydrology. Furthermore, scientists must be committed to incorporating 'societal needs' in their planning of research projects, as well as in publicizing the applications of their results, within the framework of forest-land-water policy. Alarm is expressed at the extensive disregard for the application of existing forest hydrology 'know how' in forest-land management manipulations associated with the humid tropics.

Introduction

Early in 1997, I was privileged to receive an invitation to deliver the Fourteenth Annual C.E. Farnsworth Memorial Lecture at the Faculty of Forestry, SUNY College of Environmental Science & Forestry, Syracuse. After spending the bulk of my academic career in an isolated part of tropical Australia and then suddenly having to manage a global programme, the UNESCO International Hydrological Programme, as well as taking a broader perspective of hydrology, I elected to share some of these experiences because few environmental scientists have such an opportunities. As the audience to be addressed would have varied academic backgrounds, the mandate was to keep the message topical and yet simple enough for non-hydrologists to follow. Using tropical forest hydrology as the issue, I made personal observations of selected experiences on this topic after a few years operating within the UNESCO International Hydrological Programme. I am grateful to the Editor of HESS for this opportunity to extend the contents to a wider audience.

The tropical moist forest of North-East Queensland and the Babinda catchment study

In February 1997, I returned briefly to my metaphoric research roots by attending a UNESCO workshop in Kuranda (near Cairns), in the midst of the tropical rainforest of the World Heritage area (see Fig. 1 in Goudberg and Bonell with Benzakin, 1991; Wet Tropics Management Authority (WTMA), various reports) of North-East Queensland, Australia. It was in the midst of the monsoon season and over the adjacent Coral Sea the early stages of a tropical cyclone were developing on an active monsoon trough, a seasonal feature which is positioned across northern Australia. Each night I heard the

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noise of torrential monsoon rain as up to 150 mm, disgorged from the outer edges of the cyclonic disturbance, hammered on the iron roof of my cabin. Not many years previously such downpours had required me to head into the forest to check the performance of hydrological instrumentation, as well as to collect water samples for isotopic and other chemical analyses, as environmental tracers to determine the origins of the storm runoff. Many would describe the working conditions as appalling; this extremely wet environment receives more than 4000 mm of rain a year coupled with sustained high humidities and temperatures and daily rainfalls occasionally exceeding 250 mm (Gilmour, 1975; Bonell *et al.*, 1991). Knowing that similar research had never been, nor would likely be undertaken in such a highly energetic environment, kept me investigating how these tropical forested experimental catchments function and cope with the annual rainfall deluge, more than 60 per cent of which is concentrated in the four months of the monsoon season (Bonell and Gilmour,1978; Bonell *et al.*, 1981; 1991; Elsenbeer *et al.*, 1994). What are the hydrological secrets that need to be unravelled? How relevant is such work to similar environments in the developing world which experience similarly high rainfalls? Indeed, how did the native aborigines (subsequently removed by the Europeans) survive in this relatively hostile hydrological environment?

Located on the eastern slopes of the Graham Range facing the Coral Sea (6 km east of Babinda, 17° 20′ S, 158° 58′ E), a paired catchment study was initiated in the 1960s for more practical reasons than simple scientific curiosity (Gilmour, 1975: Gilmour *et al.*,1982). Then, the Queensland Department of Forestry was pursuing a practice of unconstrained logging as one still sees today in some less developed countries. Only later did escalating opposition from the conservation movement enforce management guidelines for log extraction arising out of the results of this scientific programme (Cassells *et al.*, 1984). Subsequently, the same experiment contributed scientific evidence during the very bitter campaign between the Australian Federal Government and the Queensland State Government over the Federal Government submission for World Heritage Listing of the rainforest in 1989.

Why then, did I leave such an active research programme after nearly twenty years? With a few notable exceptions, there was surprising disinterest within the local academic community in the vision and value of technology-transfer of such research into the broader global tropical forestry perspective. A centripetal interest confined to the World Heritage area *per se* prevailed, so much so that I entered the international arena as a UNESCO environmental scientist with responsibilities for the humid tropics, hydrological processes and climate change components of the International Hydrological Programme (IHP). From hereon, I would like to outline some personal experiences within the IHP and comment on whether my personal aspirations to help improve the global situation mirror my earlier experiences in north-east Queensland forestry practices.

Tropical forests—climate variability and change issues

Since the 1980s, tropical deforestation and its adverse effects on biodiversity and climate have received enormous global publicity; less publicized are the socio-economic fundamentals causing such forest removal. For example, the book 'Saving the Tropical Forests' (Gradwohl and Greenberg, 1988), indicated that the equation of deforestation involved more than 30 variables. The overriding factor, however, is the escalation of population in the humid tropics where about one-third of the global population may well be located by the beginning of the 21st Century (Bonell *et al.*, 1993). Such escalation places tremendous pressure on the environment in general and especially on forests as poor, landless populations clear-fell for fuel wood and the subsequent growing of food crops for their survival (Gradwohl and Greenberg, 1988). In response, the International Hydrological Programme elevated the humid tropics (using the definition of Chang and Lau, 1993) as one of eight Themes of the current Fifth Phase (1996–2001) with forest hydrology being a fulcrum of activity (UNESCO, 1996).

A common question concerns the possible impact of deforestation on global climate (e.g. Henderson-Sellers *et al.*, 1995), although this issue rarely extends to surface water hydrology or the more practical needs of water resources management. Conversely, what are the consequences of global climate change on tropical forests? One of the principal conclusions from an IHP expert group was that the outputs from various General Circulation Model (GCMs) scenarios gave different (and in some cases contradictory) predictions (especially for precipitation) even for the same data sets (Shiklomanov, 1999). Notwithstanding the appreciation of the difficulties facing climate modellers, the group expressed '. . . alarm at the lack of progress in providing consistent interpretation' (UNESCO, 1995a; van Dam,1999). Whilst this comment was directed more towards the concerns of the water resource managers, the biological community is equally interested in scenario outputs for the biodiversity and fate of tropical forests. In April 1995, the World Wildlife Fund commissioned a Workshop (*Potential Impacts of Climate Change on Tropical Forest Ecosystems,* San Juan, Puerto Rico), based on a state-of-the-art GCM for the tropics (Hulme and Viner, 1995). I was asked to provide a hydrological perspective on behalf of the IHP; this appeared recently as a contribution to a Special Issue of the journal *Climatic Change* (vol. 39 (2/3), 1998, Markham, A., ed.). Because of the uncertainty described, I was able to highlight only what is known now in terms of current hydrological processes in the forests and disturbed landscapes of the humid and semi-arid tropics and, hypothetically, to transpose such knowledge to any shift in climate and the corresponding vegetation belts. Moreover in environments which currently endure high annual rainfalls, say in excess of 3000 mm, a reduction of 200 or 300 mm has little impact. It is at the margins of different forest types that the ability of tree roots to extract deeper groundwater may counter any changes in the **duration** of the dry season and consequent reductions in rainfall (Bonell,1998). These are the most vulnerable areas because any anthropogenic disturbance may destroy the fragile microclimate habitat for tree seedling regeneration, as well as the more adapted deeper rooted species.

The above point is emphasized when one examines the evergreen and mixed forests of the Western Ghats, India. Annual rainfall ranges from 2000 to 6000 mm per year, the bulk of which falls in only three or four months. The trees survive the long dry season (> 6 months) using thick deep tap roots which must extend to deep groundwater bodies. Once destroyed, these tree species have difficulty regenerating through the sealed surface soils. ***Consequently one cannot easily separate anthropogenic effects from a climate change perspective, and it is even debatable whether anthropogenic effects will have the stronger impact—certainly in the short to medium term—because of the socio-economic pressures previously mentioned.***

Unfortunately, the current generation of GCMs is unable to incorporate the impacts either of the El Nino-Southern Oscillation or of adjustments in the preferred tracks of tropical cyclones arising from climate change (Gates *et al.*, 1996, pp. 253–258). Because these phenomena have major global impacts on the present day hydrological function of forests (Bonell, 1998), in terms of evaluating the effects of climate change on tropical forests, GCMs are presently of little practical use.

Hence, the science community must become more proactive in improving GCM modelling in connection with tropical deforestation. In this regard, the Amazon basin has received considerable attention since the early 1980s. After the 'maritime continent' of the western Pacific centred on the Indonesian Archipelago, the Amazon basin is the second most concentrated energy source for driving the global atmospheric circulation (Gunn *et al.*, 1989; Manton and Bonell, 1993). Thus, weather satellite images commonly show a persistent cloud band (transferring the latent energy) extending out of the Amazon basin across the coast in the Rio de Janeiro-Sao Paulo area and then onwards into the South Atlantic. Thus, apart from the publicized concerns over biodiversity, it is recognized that broad-scale deforestation can alter the climate at least at the regional scale within the Amazon basin and even at a larger scale (Gash *et al.*, 1996). Up to now, most supporting experimental fieldwork in Brazil has concentrated on micrometeorological measurements from only one (Shuttleworth, 1988) and later three tower sites in two separate campaigns, in each of which the vertical terrestrial-atmospheric exchange of energy and water vapour by way of evaporation was monitored. No consideration was given to the surface, horizontal transfer of water and the complementary biogeochemistry except for soil moisture measurements down selected profiles (Gash *et al.*, 1996). The GCM predictions in terms of changes in precipitation and temperature, have become progressively smaller over the last decade or so. For example, the estimated reduction in basin-wide average precipitation has been reduced from about 20% to 7% for the scenario of imposed, wholescale deforestation (Institute of Hydrology, 1994; Gash *et al.*, 1996). The increasing availability of field measurements partly explains these adjustments.

The predicted rise of 2 °C in average basin-wide temperature (where there is more consensus between models) may cause an enhancement or feedback in the advection (or horizontal transfer) of moist easterlies from the Atlantic to offset some of the reduction in local rainfall recycling from the forest. More significantly, the latest GCM exercise by the Hadley Centre for Climate Prediction and Research (UK Meteorological Office) acknowledges the greater importance of the surface hydrology than was previously credited in terms of its effect on the vegetation albedo which is one of the most sensitive, land surface variables of the 24 or more incorporated in GCMs (Lean *et al.*, 1996). Previously, forest albedo had always been assumed constant; recently, it has been shown to vary with soil moisture content (Culf *et al.*, 1995). Soil infiltration and soil surface moisture distribution are now known to be much more sensitive variables in GCMs than had previously been considered (Lean *et al.*, 1996).

Since 1992, the IHP has collaborated with the International Geosphere-Biosphere Programme (IGBP)—Core Project Biospheric Aspects of the Hydrological Cycle (BAHC) in including surface hydrology on the GCM research agenda through the use of a nested-drainage basin approach (to address the problem of scale). Traditionally large-scale field experiments for GCM parameterisation have been driven by the atmospheric science community at 100 × 100 km grid scale so that many facets of forest hydrology are considered by many hydrologists to be a source of error in GCM predictions. A particular issue is the role of deep groundwater. Tropical moist forest in the Amazon basin is capable of extracting water up to depths of 18 metres or more (Nepstad *et al.*, 1994); this safeguards the forest against the prolonged dry season drought (especially in the S.E. parts of the Amazon basin). In Australia, using environmental isotopes coupled with modelling, a deep groundwater store of up to 3000 mm (120 inches) equivalent rain depth was determined recently, this sustained dry season streamflow and the transpiration demands of the forest. Remarkably, the isotopic concentration of stream water always returned to similar pre-storm background levels despite considerable variations during individual storms which in total amounted to more than 3200 mm of rain over the 4-month wet season of study, December 1990-March 1991. Such persistent background levels suggested a large seemingly 'well-mixed', deep groundwater body (see discussion of Raats, 1978 in Barnes and Bonell, 1996) which was buffered from the short-term effects of the monsoon rain (Barnes and Bonell, 1996; Bonell *et al.*, 1998). This raises the question: to what extent are deep groundwater bodies correlated with evergreen tropical forests in climates with a long dry season, such as the Western Ghats, India? Reliance by GCM scientists on estimates of surface soil moisture alone is therefore too simplistic. In addition, because few workers have measured root depths properly, the need for a better understanding of root depth characteristics presents a major research challenge (Concise Experimental Plan, LBA, 1996). Presently, in the absence of extensive root depth measurements, and to avoid undesirable modelling complications (e.g., see Table 2 in Henderson-Sellers *et al.*, 1995, p. 67), most modellers assume a fixed depth of, say 1.5–2 metres, which is now known from more recent work to be totally inadequate (Nepstad *et al.*, 1994).

All these considerations have contributed towards the planning of a multiagency, multidisciplinary research programme entitled *Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)*, originally scheduled to commence in 1998 for a 5-year period at least (Concise Experimental Plan, LBA, 1996; Integrated Science Plan, LBA, 1997). The planning of the hydrology-hydrochemistry component has been largely in the hands of the joint IGBP(BAHC)-IHP collaboration and a major funding submission was prepared for the European Union. Through a more traditional experimental catchment approach, the role of soil moisture redistribution and groundwater linked with transpiration demands will be one of the key aspects of the work. In addition, total evaporation [that is, transpiration (dry canopy losses) plus evaporation (wet canopy losses)] estimated from catchment water balances will provide a cross-check with alternative estimates using micrometeorological methods based on towers at a patch scale. As with all IHP (as well as IGBP)—supported programmes, training of local scientists and technicians will be an important component. If the LBA hydrology-hydrochemistry component fulfills even part of its original objectives, then South America in the 21st Century will be a focal point for global tropical forest hydrology expertise; this is consistent with UNESCO's objectives of enhancing the technical and scientific capacity of developing countries.

The need for long term experimental catchments

Another option to address climate variability, would be analyses of long-term forest hydrology data sets (as recommended by the IHP expert group on climate change) ; these depend on the maintenance of long-term experimental catchments. There is a paradox here, when it comes to national government policy in many countries towards such long-term monitoring sites. There is international recognition of the U.N. Framework Convention on Climate Change (UNFCCC, 1992), many scientific institutions are confronted with the short-term economic thinking in government decision-making whereby 'a short-term scientific return' (in usually 3 year cycles) has to be guaranteed for receipt of financial support. Hence, long-term data programmes are nowadays expendable in terms of economic policy and are being reduced or eliminated in many countries. Thus, **long-term** operational experimental catchment studies (forest or non-forested) in the developed world have contracted, especially those operated by non-governmental institutions such as universities. In the tropics, the situation is even more bleak and few medium to long term, data-rich experimental catchments remain there that have followed either the traditional paired catchment (Hewlett *et al.*, 1969) or the catchment water balance experiment (Blackie *et al.*, 1979) approaches. The last 12 months have marked the closure of the French ECEREX (Ecology, Erosion Experiment) in French Guyana, which was initiated in the mid-1970s (Sarrailh,1990; Fritsch, 1992). This was preceded by the progressive closure of the UK East African catchments by the early 1970s, after more than 16 years of record (Blackie *et al.*, 1979) and the later termination of the Peninsular Malaysian experimental catchments, *viz*, the Sungai Tekam (DID, 1989; Abdul Rahim, 1988) and the Berembun Forest Reserve (Negri Sembilan) (Abdul Rahim and Harding, 1992; Abdul and Yusop, 1994; Yusop and Suki, 1994). Only the Babinda catchments in North-East Australia, survive from the International Hydrological Decade era, albeit operating only at a basic level through an IHP initiative. More recent initiatives such as the Mendolong paired catchment study in Sabah, Malaysia (Malmer, 1993, 1996; Malmer and Grip, 1994; Grip *et al.*, 1994), the Bukit Tarek catchment (Noguchi *et al.*, 1997a, 1997b) near Kuala Lumpur and the Bisley experimental catchment in the Luquillo mountains of Puerto Rico (Scatena, 1989, 1990; Scatena *et al.*, 1993) may, in part, substitute for the closures elsewhere.

Whilst these more recent developments are being supplemented by shorter term catchment initiatives, mostly in Latin America, *the longer term programmes are the focal points for addressing the hydrological impacts of various forms of forest conversion as well as of climate variability; the duration of the recent experiments remains too short to assess, comprehensively, long term, land degradation impacts following forest conversion as well as climate variability over several decades. Moreover, the number of longer term projects connected with tropical forests still remains very limited, in a region which experiences some of the worst examples of forest land management arising from intense socio-economic pressures.* Much dependence has to be made on the few long-term experiments for developing forest land management guidelines, but which are not widely enforced across the humid tropics.

Hence, in response to the above issues, the IHP will join forces in August 2000 with the International Union of Foresters Research Organization (IUFRO) in a Symposium and Workshop *'Forests-Water-People in the Humid Tropics: Past, Present and Future Research for Integrated Land and Water Management'*. This forum will synthesize all tropical forest hydrology research, including all aspects of disturbance and conversion impacts and will also encourage new long-term catchment initiatives to address practical people-water-forest issues at both the national and international level. Such initiatives, however, must be focused on scales larger than the those associated with most existing experimental catchments (traditionally at the micro-scale, < 10km^2), at least up to the mesoscale (10–10 000km^2) or higher (Dooge, 1986; Bonell, 1993; Concise Experimental Plan, LBA, 1996). While previous micro-scale studies have determined best management practices for tropical forests (e.g. Cassells *et al.*, 1984), it is at the larger scales that the impacts on the hydrology of climatic phenomena, such as the El-Nino-Southern Oscillation (e.g. Richey *et al.*, 1989; Poveda and Mesea, 1997 in South America) must be addressed to improve water—land management policy.

A significant proportion of the joint IHP/IUFRO activity will be devoted to interfacing 'the science' with the perspectives and requirements of societal needs through the involvement of policy makers, economists, resource managers and local community leaders. The support of these groups must be secured before any new scientific programme is adopted. The new Regional Centre for Humid Tropics Hydrology and Water Resources of South East Asia and the Pacific in Kuala Lumpur will play a significant role in organizing this joint IHP-IUFRO venture, whilst at a global level, the embryonic Global Terrestrial Observation System (GTOS, 1998) and the UNESCO-led multiagency programme *Hydrology for Environment, Life and Policy (HELP)*, might act as catalysts towards these efforts.

The hydrological impacts of reforestation and rehabilitation of degraded lands: a visionary focus

Whilst global attention is focusing on tropical deforestation, selected Indian State forest services in the Western Ghats are experimenting with various reforestation strategies on degraded lands using indigenous hardwoods as well as exotics such as eucalyptus. At the invitation of the Karnataka Forestry Department, the IHP is evaluating the impact of reforestation on the surface soil infiltration rates and subsoil hydrological properties in preparation for the establishment of a second-phase catchment hydrology programme (UNESCO, 1997). A principal objective of the current work is to test the hypotheses that deforestation in the humid tropics increases flood peaks and, conversely, reduces dry-weather flow, which has significant implications on local community water supply (Bruijnzeel, 1989; Pereira, 1991; Bonell, 1998). The few controlled catchment experiments are not representative of the long-term degraded lands where human impacts have been sustained for decades into centuries; either the converted forest was replaced by an alternative crop or the experiment continued for only a short period after tree felling. In such cases, there were consistent reports that the principal increases in water availability in dry weather flow were from savings in transpiration as found elsewhere in humid temperate work (Bruijnzeel, 1990; 1996). Thus, this IHP initiative in India is the converse of the 'calibrate, cut and publish' paired catchment approach; it is the time lag in ecohydrological recovery of degraded land through the use of various reforestation strategies (UNESCO,1997) which is being evaluated.

When UNESCO was established over 50 years ago, part of its mandate was to establish ***long-term programmes*** to address some of the most challenging problems. Free from the severe 3-year economic cycle of research funding, UNESCO retains a unique position of being able to inject some much-needed long-term vision into its projects at a time when this is becoming a rare quality elsewhere. For example, over 30 years ago, the critical issues related to water were insufficient knowledge of available water resources (and associated water balances) which prompted the UNESCO International Hydrological Decade (IHD), 1965–1974, the predecessor of the IHP (UNESCO, 1969; 1974). That visionary initiative stimulated long-term monitoring of basic hydrological variables for improved water resources (and related forest land) management. The IHD also encouraged research into hydrological processes, which was a major step towards the later development of physically-based models. The long-term benefits of the IHD are now being realized as a basis for evaluating the impacts of climate variability and land-use change on the hydrology, and consequently water resources management; more especially in the data-rich extratropical regions, through the UNESCO FRIEND programme (*Flow Regimes from International Experimental and Network Data* (Gustard *et al.*, 1997). The IHD also stimulated advances in land-use hydrology such as monitoring the hydrological impacts of forest conversion. Similarly, the prospective establishment of long-term experimental drainage basins to evaluate the *impacts of reforestation of degraded land* which is linked with other interdisciplinary activities in forestry, soil biology, biodiversity and socio-cultural aspects, is one such long-term vision. People will always need forest products and they need high quality water; thus, repairing the landscape is an important step towards ensuring both such needs.

The socio-cultural dimension

The Western Ghats project is strongly dependent on local communities in the plant nurseries and subsequent silviculture of reforestation. Unlike the accepted emergence of social forestry (see for example Gilmour and Fisher, 1991), hydrology in general has been slow to incorporate social and cultural aspects within the practical implementation of water science, that is, the parallel development of **social hydrology** as a systematic area of study. Perhaps the strong technological base with its roots in engineering has stalled much progress towards the social aspects. Surprisingly, the symbiotic working relationship between foresters and forest hydrologists has not encouraged much progress in this area. And yet the practical implementation of field projects in the developing world of the tropics may well fail without the knowledge, participation and support of the local communities.

In the Western Ghats, community awareness is being achieved through the efforts of the Karnataka Forest Department but, elsewhere e.g. in the South Pacific, the recently initiated IHP field projects are attaching social scientists and community forestry NGOs to work alongside the hydrologists to ensure the people-water-forest benefits are achieved and understood (UNESCO, 1995b). I learnt much as a hydrological consultant watching the social foresters help implement the Nepal-Australia Forestry Project in the mid-1980s. To press home the point, during the course of evaluating the feasibility of a forest hydrology catchment programme in the Solomon Islands, one quickly appreciates that, unlike in western countries, the setting aside of a forested catchment for experimentation is not simply just getting permission from a Government Forestry Department. The Melanesian culture is strongly based on land tenure. One is faced with a complex, patchwork quilt of individual land tenure. To guarantee both permission and security of experimental tenure (in the face of logging threats) requires metaphorically 'a carpet' of social forestry-community awareness work to be pre-laid and conducted by NGOs before forest hydrology experimentation is proposed. Part of the NGOs' task is to convince the local people of the sustained alternatives in terms of forest products and so to persuade them not to let the logging companies on to their land, otherwise any long-term hydrological monitoring is ruined. Furthermore at the planning stage, the benefits arising out of the implementation of a forest hydrology programme, such as the maintenance of a sustained clean water supply have to be explained and understood at the local community level. The close involvement of the community during hydrological monitoring introduces the notion of 'ownership' as well as a vested interest in the security (e.g. protection of instrumentation) and therein lies the ultimate success of the project. Technical training should also be part of this process.

There is another interesting aspect to the social and cultural attitudes to forests and water which is being currently fostered by the IHP. As part of community surveys by hired social scientists, questions are being asked centring on traditional knowledge of water and forest management. The aim is to provide clues or insights into the workings of the environment under consideration which raise issues for further research using more sophisticated technology (UNESCO, 1995b). For those that dismiss this approach, one needs to be reminded of the so-called myth—now being taken more seriously as a research topic—that in selected situations deforestation could increase floods and decrease dry-weather streamflow, as was outlined in the Karnataka project of India. Another 'myth' that forests 'attract' more rainfall may also now have some validity in selected environmental situations, especially where vertical wind shear is weak; this provides the basis for convective cloud development in unstable conditions (often found in the tropics). Recent modelling and sensitivity experiments based on a large-scale field experiment conducted in the late 1980s in south-west France (HAPEX-MOBILHY) supports, for *a specific case of boundary conditions,* the notion of a 30% increase in rainfall with a full forest cover compared with a bare soil domain (Blyth *et al.*, 1994). Several process mechanisms are involved here. For example, a negative (downward) sensible heat flux immediately above the forest canopy provides the necessary energy for wet canopy evaporation during rainfall. The enhanced (positive-feedback) wet canopy losses immediately after rainfall are augmented by the effect of greater aerodynamic roughness of the forest canopy enabling increased transpiration from the deeper-rooted forests compared with short cover crops. Thus, a larger volume of water vapour is potentially available for cloud development at a mesoscale.

Recent reports in the scientific literature have highlighted the greater importance of rainfall recycling than previously credited in the Sahel of West Africa (Savenije, 1995; Gong and Eltahir, 1996) following earlier reports for the Amazon basin (Salati *et al.*, 1979; Eltahir and Bras, 1994). Elsewhere, Pielke *et al.* (1997, 1998) demonstrated the reorganization of the temporal and spatial occurrence of rainfall at the mesoscale arising from changes in the energy balance due to various types of land use conversion. In the HAPEX-SAHEL (Gouterbe *et al.*, 1994, 1997) the impact of land use changes on the energy balance, and therefore in rainfall occurrence, were possibly more influential during the opening and closing stages of the wet season when weak convection events are dominant (Dolman *et al.*, 1997; Le Barbe and Lebel, 1997). More recently, model simulations by Zheng and Eltahir (1998) indicate that the meridional conditions of the land surface as characterized by vegetation cover and soil moisture can play a significant role in the dynamics of the West African monsoon and rainfall variability. Significantly, the most sensitive region to vegetation cover changes is along the humid, southern coast where forest conversion (deforestation) has already been extensive. The resulting reduction in surface net radiation and total flux of heat from the surface is capable of reducing, dramatically, the monsoon circulation (Zheng and Eltahir (1998)); these writers attribute coastal deforestation as a supplementary drought producing mechanism to that of the much publicized Sahelian 'desertification'. By contrast, the monsoon circulation is less impacted by land surface cover changes further north over the Sahel and border areas of the Sahara Desert (Zheng and Eltahir, 1998).

The possible extension and generalization of the above phenomena to other tropical environments of varied surface cover is a critical issue for research.

This discussion also reinforces the need for greater consideration being given to the impacts of land use change on the energy and water balances up to the mesoscale; and will be a focal point for attention in the forthcoming LBA project.

The North East Queensland experience within the international setting

Moving towards an overall synthesis, I return to my opening statements on my personal research experiences in Australia and ask if they are just a mirror of what is happening elsewhere within the context of managing an international programme. The prime reason for the Australian research was to monitor the damaging effects of commercial logging. If commercial logging is to proceed (which I personally do not necessarily condone) for legitimate reasons in the quest for hard currency, then selectively extracting trees with minimal environmental damage is the critical objective. It took over 12 years for the Queensland Department of Forestry to recognize and adopt in their forestry operations the recommended logging guidelines which emerged from the north-east Queensland forest hydrology research programme because it increases costs of extraction (Cassells *et al.*, 1984). They were eventually incorporated by the Queensland Department of Forestry for two reasons: (i) a slow attrition of scientific publicity from the researchers (even at the risk of losing their donor support) and (ii) the imminent escalation in conservation pressure for all logging to be banned and for formal protection of the forest. The research was also publicized through the Asia-Pacific through close links with the East-West Center, Honolulu. Subsequently the International Tropical Timber Organization (ITTO, 1990) in Yokohama adopted the Queensland Department of Forestry forest management guidelines as a global standard and have since gone to great lengths to publicize them. And yet when dealing with issues put to the IHP, one sees the same devastating methods of logging, extraction continuing (to avoid additional economic costs) being implemented in the western Pacific and west Africa for example, and I even read of similar reports from selected areas of Latin America. When in one of the south-west Pacific countries, I was requested by the local scientists that the IHP should support forest hydrology research solely to develop logging guidelines. The stimulus was to find a solution urgently for the current level of appalling environmental damage being achieved in certain areas by foreign timber companies in their quest for rapid log extraction. When I replied that the knowledge already existed, and therefore research on these grounds alone could not be justified, there was a reaction of utter disbelief (note that there were other scientific reasons to establish a research programme to maintain the interest of donors).

Concluding comments

One is confronted globally with the practical dilemma of short-term economic gain in the form, for example, of commercial logging at the expense of the environment; where the practical implementation of **existing scientific know-how** is conveniently ignored. Thus, the short-term, monetary profit motive wins out over the incorporation of research outputs. ***The fundamental question then is where does this put the real value of forest hydrology research within the context of non-implementation in many developing countries?—a question all environmental scientists should now be obliged to consider.*** Ensuring a correction to this situation is highly complex and a formidable challenge which goes beyond the immediate boundaries of science *per se*, and involves social and politico-economics within the sphere of high level policy and decision-making. Even more of a concern, is that there is a scarcity of experienced hydrologists in general (and not just forest hydrologists) who have also a good grounding in high level policy and decision-making to take on the above issue, and at the same time protect the interests of water science in its broadest aspects. Since the IHD era we have had to acquire additional literacy beyond hydrology in other areas such as mathematical statistics, computer applications (including software management) as well as GIS in the context of data processing and interpretation. Perhaps we are now coming to the point where the socio-cultural and policy-making aspects of water and land management should also become a complementary component to water science based curricula, like social forestry is in most university forestry courses. Whilst not directly connected with forest hydrology, one refers to recent publications connected with food security (Falkenmark *et al.*, 1997; Falkenmark and Lundqvist, 1998; Wallace and Batchelor, 1997), surface and groundwater quality (Falkenmark and Lundqvist, 1998; Hilding-Rydevik and Johansson, 1998) and societal water needs (Falkenmark, 1997) which provide examples of interfacing hydrology with water-land management and policy.

Within the more affluent countries, an alternative 'ethical' approach is currently being advocated and debated between the scientific and social science communities. This approach is based on the notion that rather than imposing environmental protection through legal instruments, each stakeholder is pledged to 'a code of ethics' whereby there is a moral obligation to maintain certain rules of conduct in environmental manipulation in order to maintain natural resources in a 'sustainable' condition for passing on to future generations. Similar arguments are being put forward to support the need for long-term monitoring to counter the adverse, economic rationalist position which currently prevails in many developed countries (Hilding-Rydevik and Johansson, 1998).

Elsewhere, my experience dealing with policy-makers in a Regional Development Bank (which can exercise considerable political and economic muscle in environmental management) is that there is a major gulf in the language that they speak and the one that we are accustomed to using in mainstream university research. Finding ways to bridge that gap would be a step forward in order to highlight the importance of research and implement its findings at such a high level of policy making. Nonetheless the preceding issues lead to the point that for continued support for environmental scientific research, such as forest hydrology, the question should be asked: whether the mainstream research system can continue to focus mostly on the publish or perish syndrome *per se* without being coaxed into requiring some longer term vision of practical value as well. (I do not think that we can continue doing science just as a hobby and gaining individual pleasure at watching our CV publication listing progressively expand. Also I think that there is a point in one's scientific career where one should contribute something to the betterment of environmental management.) One such vision is directing our efforts towards societal-forest-water issues, coupling the extension of good science within socio-cultural and economic dimensions whether it be, for example, in commercial logging, reforestation of degraded lands, or agroforestry. A particular challenge is the quantification of Indicators of Sustainable Development (ISDs) (Dahl, 1996; SCOPE, 1995) to help policy makers test the validity of actual values of ISDs and move beyond the notion of Sustainable Management, much-vaunted in international gatherings but merely 'an article of faith', with presently no general consensus on a clear or workable means for implementation. ***Such work would also help address the burning question whether in the long term in developing countries, economic development (as we know it on Western industrial lines) is reconcilable with sustainable management.***

'Water' will be the key environmental issue of the 21st Century in terms of its scarcity in both quantity and quality (as a potable supply) because of the escalation in socio-economic pressures. The forests of the humid tropics, especially the montane forests (including cloud forests, Bruijnzeel and Proctor, 1995) are the prime source of the most potable, surface water supply. There is then a common vested interest both in forestry and hydrology for the appropriate management of tropical forests to guarantee a wide variety of forest products and conservation of biodiversity as well as ensuring a high quality water supply. Moving towards a multi-disciplinary, integrated approach which is set within a drainage basin framework is a tool for achieving such objectives.

It is in such areas that the IHP Humid Tropics Programme progressively incorporates these practical considerations to attract donor interest while helping to protect continued progress in forest hydrology research. Persuading some scientists to think along these lines for their own survival, however, is not always successful, herein lies one of the micro-policy challenges.

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