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A HYDROLOGICAL APPROACH TO TROPICAL FORESTATION: CONTROVERSIAL ISSUES AND POSSIBLE APPLICATIONS OF TOPOGRAPHIC-WETNESS MODELS

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BONELL, M. & MOLICOVA, H. 2003. A hydrological approach to tropical forestation: controversial issues and possible applications of topographic-wetness models. This paper provides a state of art in the field of hillslope hydrology in respect to knowledge and representation of soil moisture patterns across a river basin. It is a field-orientated review which argues for a stronger input of hydrological sciences in land and forest management. It will outline the elementary aspects of topographic-wetness models which could be linked with various forestation strategies of degraded land within a drainage basin context. An implicit assumption is that there are very limited hydrological data bases available within the humid tropics. Nonetheless, these models can be applied provided detailed topographic information is available which enables the estimation of topographic or wetness indices. An alternative, experimental approach of "gauging" the spatial soil moisture pattern is proposed. A succinct coverage of the relevant hydrological processes is given and linked to the controversial hydrological issue of reports of increased flooding and conversely decreased low flows within streams emanating from degraded lands. The role of forestation in this controversial issue will be highlighted. A considerable proportion of this work was devoted towards the restoration ecology community gaining a better appreciation of the application of topographic-wetness models within the above integrative drainage basin context.

Key words: Tropical forest hydrology - hillslope hydrology - soil moisture pattern - afforestation - reforestation

BONELL, M. & MOLICOVA, H. 2003. Pendekatan hidrologi untuk penghutanan hutan tropika: isu kontroversi dan kemungkinan penggunaan model topografi-kelembapan. Kertas kerja ini melaporkan tahap pencapaian hidrologi cerun bukit dari segi pengetahuan dan gambaran corak kelembapan tanih merentas lembangan sungai. Kertas kerja ini merupakan ulasan yang berasaskan lapangan dan menghujahkan tentang keperluan input sains hidrologi yang lebih kukuh dalam pengurusan tanah serta hutan. Kertas kerja ini menggariskan aspek asas model topografi-kelembapan yang dikaitkan dengan pelbagai strategi penghutanan tanah ternyahgred dalam konteks lembangan saliran. Pangkalan data hidrologi adalah sangat terhad di kawasan tropika lembap. Bagaimanapun, model ini dapat diguna asalkan terdapat maklumat topografi terperinci yang membolehkan anggaran indeks topografi atau indeks kelembapan dibuat. Satu pendekatan alternatif dicadangkan untuk mengukur corak kelembapan tanih ruang. Proses hidrologi yang berkaitan turut diliputi dan dikaitkan dengan isu hidrologi yang kontroversi iaitu kejadian banjir yang meningkat serta aliran rendah yang berkurangan di sungai yang terbit daripada tanah ternyahgred. Peranan penghutanan dalam isu kontroversi ini diketengahkan. Sebahagian besar kertas kerja ini menekankan bagaimana pemulihan komuniti ekologi semakin diterima dalam penggunaan model topografi-kelembapan dalam konteks integrasi lembangan saliran.

Introduction

At headwater drainage basin scale ($\leq 10 \text{ km}^2$), both surface (Beven *et al.* 1995) and bedrock (McDonnell *et al.* 1996) topographies, through gravity, more often exercise stronger control than soil heterogeneity in terms of the movement and spatial organisation of soil moisture, notably in the subsurface layers and groundwater. Such topographic controls particularly apply to heterogeneous soils that are shallow relative to the hillslope scale. The first objective of this paper is to highlight such spatial organisations in these hydrological components. When linked with a digital elevation model (DEM) and a geographic information system (GIS) (including overlays of the geomorphology and soils) these components provide a basic framework for selecting the most appropriate tree species for planting as part of an overall reforestation-afforestation strategy (from here after known as forestation[1]) of degraded land. In this context, this field-orientated review calls for a stronger input of hydrological sciences into land and forest management, especially connected with restoration ecology in the humid tropics. The definition of humid tropics is that described by Chang and Lau (1993) and includes humid, subhumid and wet/dry zones.

A second objective is to emphasise that the rehabilitation of degraded lands will also address a current controversial issue in tropical hydrology. A popular belief is that forest conversion increases the occurrence of floods during storms and, conversely, decreases "dry weather" flow (delayed flow or baseflow, see Glossary of Terms in Chorley 1978). Dry weather flow has significant socioeconomic ramifications in terms of securing a reliable community water supply during dry season. Existing controlled experimental catchments refute such notions, but this popular belief has credibility under certain circumstances (Bruijnzeel 1989, Bonell 1993).

The paper outlines the principal assumptions of topographically- and physically-based hydrologic models (or topographic-wetness models) within the context of variable source area concept of runoff generation (Cappus 1960, Hewlett 1961a, b, Hewlett & Hibbert 1963, 1967). Detailed reviews of these digital terrain models for runoff production, including their mathematical basis, have been presented elsewhere (e.g. Moore *et al.* 1991, Bonell & Balek 1993, TOPOG—O'Loughlin 1990a, b, TOPMODEL—Beven *et al.* 1984, 1995, Beven 1997). Consequently, the

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[1] After Wiersum (1984), strictly speaking the term "afforestation" should be used for the planting of trees in areas where forest is naturally absent, as opposed to "reforestation" for previously forested, and subsequently degraded areas. To avoid semantic problems, following Scott *et al.* (pers. comm.) the term "forestation" is used throughout this paper.

present paper will confine its attention only on the basic elements, or outputs, from topographic-wetness models which are of particular value to tropical environments that usually have very limited hydrologic data bases. At first, it will be necessary to provide a succinct overview of the essential elements of hillslope hydrology using the appropriate terminology, as defined in Chorley (1978). We emphasise the theoretical capacity of topographic-wetness models to create the powerful framework for decision making relative to landuse conversion. An alternative approach was based on a statistical evaluation of point-soil water content across catchment (Grayson & Western 1998). The latter can be used to verify model predictions on moisture status evolution across the catchment and/or to provide outputs of the same nature. Another example regarding seasonal simulations of moisture status (Western *et al.* 1999) is also given. This example, however, refers to temperate climate conditions and, therefore, its outputs have to be reconsidered for the humid tropics.

Two detailed examples of the application of topographic-wetness models in humid tropics are discussed in respect to field hydrological evidence of given stormflow events (Molicova *et al.* 1997, Vertessy & Elsenbeer 1999).

Subsequently, this paper will outline the role of forestation and rehabilitation of degraded landscape within the context of forest removal and effects on stormflow and dry weather flow (delayed flow) during the dry season.

The variable source area concept

As part of the variable source area concept of runoff generation (Cappus 1960, Hewlett 1961a, b, Hewlett & Hibbert 1967), hydrometric studies in 1970's established that the above concept provided a spatial framework for determining the preferred areas of runoff generation in humid temperate forests by saturation overland flow and subsurface stormflow (Dunne *et al.* 1975, Beven & Kirkby 1979). The prevailing low short-term rainfall intensities coupled with very high surface infiltration rates, due to the continued incorporation of organic matter, precludes the occurrence of infiltration-excess overland flow in such forests. Even in closed-evergreen tropical forests, where short-term rainfall intensities can be an order of magnitude higher, the runoff mechanism of overland flow would seem to be limited in spatial and temporal occurrence (Bonell 1993, 1998a, b, Elsenbeer & Vertessy 2000). Otherwise, subsurface stormflow characteristically moves either downslope approximately parallel to the surface topography above a subsoil impeding layer of lower permeability or at the interface with deeper bedrock topography (Mulholland 1993, Peters *et al.* 1995, McDonnell *et al.* 1996).

Subsurface stormflow is supplemented by saturated (saturation-excess) overland flow where rain makes contact with pre-saturated surfaces arising from shallow water tables emerging at the soil surface coupled with return flow of subsurface stormflow to the surface (Chorley 1978). Saturated areas closely correlate with riparian wetlands, topographically convergent areas and the lower reaches of slopes in general, especially those having concave profiles. Saturation-excess overland flow can occur on mid-slope hollows with more shallow soils.

The above description focuses on within storm, runoff generation processes connected with the importance of dominant flow pathways to organised drainage and the storm hydrograph (stream discharge over time, L^3t^{-1}, during a storm). More pertinent perhaps to forestation is the mechanism of moisture redistribution in between storms. From a hydrological standpoint, the spatial organisation of different tree species is more likely controlled by the maintenance of optimal soil moisture and groundwater requirements in prolonged dry periods, rather than the temporal and spatial occurrence of stormflow pathways. The classic field experiment of Hewlett and Hibbert (1963) demonstrated the importance of sustained, lateral unsaturated (soil moisture) flow within soil on a 40% slope. The dominance of unsaturated, lateral flow in between storms within even unlayered (homogeneous) soils are due to changes in surface boundary conditions related to soil physics of the drainage phase (McCord *et al.* 1991, Jackson 1992). In contrast, during rainfall, infiltration and percolation are nearly vertical in hillslopes with deep homogeneous soils. Significant lateral downslope flow occurs during wetting only in layered soils with an extremely high anisotropy ratio of 10 or greater (Bouwer 1966).

Digital terrain models for runoff procedure: topographic-wetness models

Inspired by hillslope research progress, spatial hydrological models have progressively evolved following early pioneering work by Beven and Kirkby (1979) and O'Loughlin (1981). They resulted into two major modelling concepts TOPMODEL (a TOPography-based hydrological MODEL) (Beven *et al.* 1984, 1995) and TOPOG[2] (O'Loughlin 1990a, b) which are both succinctly presented. Significantly, the TOPMODEL school was influenced by the shallow soils associated with glacially-affected landscapes of the Pleistocene in the United Kingdom. On the other hand, TOPOG originated from the hydrology of duplex soils which occur extensively within south-east Australia (O'Loughlin 1981, 1986). These duplex soils are characterised by a relatively shallow B horizon of extremely low permeability.

Topographic-wetness models have been developed with a twofold purpose: (1) in predictive mode to provide design or management information and (2) in investigative mode. Thus, the mutual integration of field evidence and simulated data can advance the knowledge on hillslope processes and their representation within the mathematical models. The present generation of topographic-wetness models are in fact a free assemblage package of ideas and concepts, which under optimal circumstances can be considered as physically-based models (Beven *et al.* 1995). Their modular structure has been kept simple enough to take into account particular environmental conditions pertaining to each application. Furthermore,

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[2] TOPOG is used in the generic sense to include all software that is used to model hydrological response. It is the "root" (known as the kernal) module developed to calculate the topographic attributes essential for modelling the impact of landuse change in natural terrain (O'Loughlin *et al.* 1989) with various supplementary process hydrology modules (see Vertessy *et al.* 1996, Vertessy & Elsenbeer 1999).

the technical framework is compatible with GIS, which is a powerful tool in the field of data storage, processing and output creation. Thus, beyond the scope of classical conceptual models, the present generation of topographic-wetness models create an active research field with a strong potential to achieve significant progress in our knowledge on water-related processes. This progress meets urgent needs in resolving increased environmental problems including extensive soil degradation.

Several recent research outputs that have incorporated current state-of-art in modelling techniques and knowledge of hydrological processes in selected "long-term" experimental catchments (Molicova *et al.* 1997, Vertessy & Elsenbeer 1999, Western *et al.* 1999) have focused on stormflow processes. Therefore, they are of less concern with respect to forestation strategies which are associated with soil moisture persistence over long rainless periods. Using THALES, modelling framework based on distributed wetness index (Moore & Grayson 1991), the field-orientated modelling study by Western *et al.* (1999) was able to take into account evaporative fluxes which seem to govern the soil moisture distribution during dry periods. This approach is relevant for forestation strategies. However, since Western *et al.* (1999) conducted research in temperate climate conditions and connected with duplex soils, the scope of outputs presented below needs to be verified with respect to tropical environments with more deeply weathered soils. When concerning the latter, reference will be made to early findings from the MARVEX (MAhurangi River Variability EXperiment, 46.8 km^2), in New Zealand, which presents contrasting spatial and temporal organisation of soil moisture (Woods *et al.* 2001) from those environments associated with duplex soils (Grayson *et al.* 1997) and former glaciated landscapes (Beven *et al.* 1995).

The topographic-wetness models are based on the notion that, ultimately, morphology controls water flow pathways. This concept has received support both theoretically (Zaslavsky & Sinai 1981) and experimentally (Hewlett & Hibbert 1963). This is because lateral flow occurs widely even though the conceptual model of delivery mechanisms of hillslope runoff varies across selected environments (Beven 1986). Implicit to this morphological control is the existence of a soil impeding layer to vertical percolation which, therefore, encourages a shallow water table and lateral, subsurface stormflow. Thus, on the basis of humid temperate experience it is assumed that the soil is of finite depth and that the hydraulic conductivity is negligible at the base of the profile. In the humid tropics, such an assumption only partially holds in selected environments (e.g. Bonell 1998a, Elsenbeer & Lack 1996, Elsenbeer *et al.* 1999, Elsenbeer & Vertessy 2000). For the most part more deeply weathered regoliths exist which cause a more complex hillslope hydrology linked with the role of macropores and deeper ground water bodies (referred to later) (Bonell *et al.* 1998). Nonetheless, there is a general trend of decrease in hydraulic conductivity with depth, as one progresses away from the highly permeable surface layer associated with the profusion of roots and incorporation of organic matter (Elsenbeer & Vertessy 2000).

The role of morphology allows the assumption that hydraulic gradient of shallow water table (above the subsoil impeding layer) can be approximated by local topographic slope (tan β). Considerable discussion has occurred on what assumption to make regarding the most appropriate mathematical expression to represent the vertical decrease in hydraulic conductivity with depth. In TOPMODEL, Beven *et al.* (1995) assumed an exponential relationship for both field saturated hydraulic conductivity (Lt^{-1}) and the related transmissivity (L^2t^{-1}) parameter whereas in TOPOG, O'Loughlin (1990a, b) adopted a constant relationship for field saturated hydraulic conductivity. In the latter, hydraulic conductivity takes a fixed value and then abruptly changes to zero at the subsoil impeding layer. Ambroise *et al.* (1996) presented a detailed review of those options including the addition of a linear relationship for field saturated hydraulic conductivity. In contrast, Molicova *et al.* (1997) confirmed the exponential assumption of Beven *et al.* (1995) for a tropical moist forest catchment study in French Guyana. An additional assumption is that the dynamics of saturated zone can be approximated by successive steady representations using TOPMODEL (Beven *et al.* 1995), although an unsteady state component can now be managed by TOPOG (Vertessy & Elsenbeer 1999). The latter is more relevant to catchment water yield and stormflow studies than to the simpler applications described here.

Whichever model is used, either TOPMODEL or TOPOG, an analysis of the catchment topography using a digital elevation model (DEM) precedes the overlay of the hydrology component (reviewed in Bonell & Balek 1993). The DEM divides the topography into flow segments to calculate a topographic index in TOPMODEL (Quinn *et al.* 1991, Beven *et al.* 1995) or a wetness index in TOPOG (O'Loughlin 1986). While developing the topographic-wetness framework, one has to assume that the given catchment belongs to the same rainfall field and so that all the pixels receive the same amount of water. Otherwise, the non-homogeneous inputs of water across a catchment rainfall field will offset the soil moisture pattern predicted by the topographic-wetness index map (Molicova *et al.* 1997). This can be the case of forestation catchment studies which can cover large areas, especially under the humid tropics; here the convective nature of rainfall cells engenders an increased variability on rainfall/throughfall fields. Then the different rain field zones have to be analysed separately. Goodrich *et al.* (1994) for example noted that the spatial and temporal distributions of short-term soil moisture were more dependent on the spatial movement of convective rainfall fields than on non-local topographic (lateral flow) or local (vertical flow) controls. An example of the spatial organisation of the topographic index for the French Guyana study by Molicova *et al.* (1997) is given in Figure 1.

Elsewhere in the MARVEX study, Woods *et al.* (2001) assessed the movement of rainfall fields linked with the spatial and temporal variability of runoff over the 46.8 km^2 drainage basin using a combination of radar imagery and a relatively dense hydrometric network. The authors determined that one hourly integrated rainfalls as most appropriate to best fit the rainfall-runoff relationship, with runoff lagging rainfall by about one hour. In the humid tropics, where short-term rain (say one to six minutes) intensities are one order of magnitude higher, shorter-term rainfall resolutions are considered better in describing the time lag of the rainfall-runoff relationship within sub-basins of catchments having similar size to MARVEX.

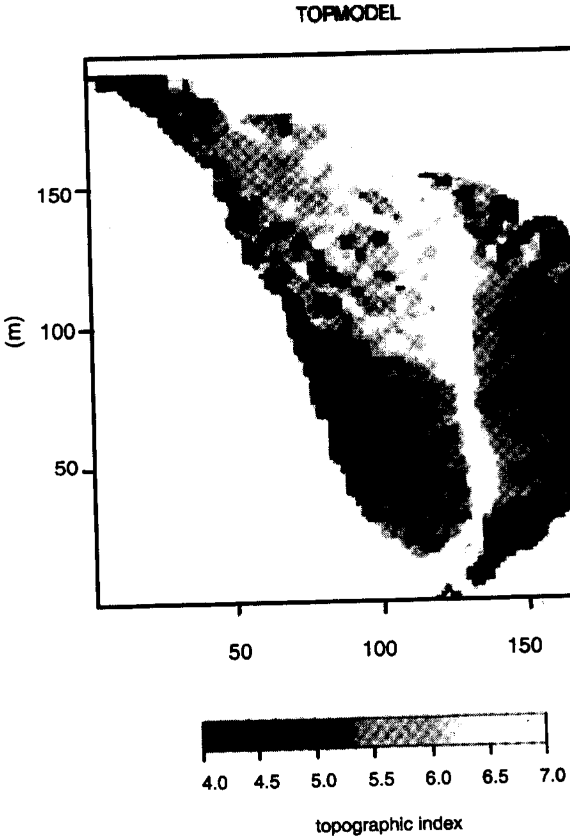

Figure 1 Spatial organisation of the topographic index for the French Guyana (ECEREX catchment B) study (Molicova *et al.* 1997)

The water-related, topographic or wetness indices outlined above effectively determined the areas most liable to soil waterlogging and indicated the preferred areas for runoff generation. Further, the assumption of water tables being approximately parallel to the surface enables such models to incorporate the effects of topographic divergence and convergence. It is within the topographically convergent areas where soil-water movement generally is concentrated, thus giving higher soil moisture volumetric contents. In the case of TOPMODEL, the higher values of ln $(a/\tan \beta)$ indicate greater potential for the development of saturation (Figure 1). High values of ln $(a/\tan \beta)$ occur at locations where large upslope areas (developed from the flow strips developed by the DEM) are drained (high values of a), and where the local gravitational gradient is low (low value of $\tan \beta$). The topographic index, ln $(a/\tan \beta)$, is the basic equation for use in rehabilitation/ forestation strategies and only requires a topographic map as baseline information for inputting into a DEM for deriving the spatial distribution of ln $(a/\tan \beta)$. Linked with the topographic index, is the development of an equation to describe the depth of the water table (Beven *et al.* 1995) which has particular practical value in rehabilitation/forestation strategies. This equation, however, does require some hydrological parameterisation, e.g. field saturated hydraulic conductivity, and is most suited to an experimental catchment study evaluating the impacts of various forestation strategies. The same equation, however, does not manage deeper groundwater especially associated with deeply weathered tropical regoliths (Quinn *et al.* 1991). These groundwater bodies help sustain the transpiration requirements of mature forests during persistent drought (Bonell 1998a).

Restrictive assumptions and limitations

It is important that potential users of the described models appreciate the ramifications of their assumptions and their limitations, so that they do not necessarily accept the spatial distribution of the calculated topographic indices at face value. The initiators of TOPOG (O'Loughlin 1990a, b) and TOPMODEL (Beven *et al.* 1995) acknowledge the restrictive assumptions and limitations of these models. They work best where there is a quasi-parallel water table to the topographic surface. Also the water table depth is controlled mostly by topography, and not bedrock geology (McDonnell *et al.* 1996) and the soil transmissivity decreases exponentially (Beven *et al.* 1995) or linearly (O'Loughlin 1986) with depth. Any violation of these assumptions particularly affects the storm runoff generation modelling component (Beven *et al.* 1995, Bonell 1998b), which is of less concern because access to optimal soil moisture or groundwater during prolonged periods of water stress arising from drought may be the more important criterion.

The humid tropics is commonly associated with deeply weathered regoliths which encourage deeper, permanent groundwater bodies (e.g. Quinn *et al.* 1991). Transient saturation within the upper soil horizon, however, can still occur during storms (Molicova *et al.* 1997, Bonell *et al.* 1998). Thus the appropriate representation of the deeper groundwater in TOPMODEL, for example, continues to pose problems in a Côte d'Ivoire catchment area (Quinn *et al.* 1991). Consequently the topographic index is affected because of the morphology of the permanent water table, which does not necessarily reflect surface topography. Related to this issue, McDonnell *et al.* (1996), in a humid temperate study, demonstrated three-dimensionally that topography is not always the control of subsurface hydrological flow at hillslope scale. They suggested that the "topography" of the soil-bedrock interface exercised more control on subsurface stormflow, which requires some geotechnical survey to provide such information for recalculating the topographic indices. However, in between storms the redistribution phase of moisture was more closely linked with surface topography (Hewlett & Hibbert 1963, McDonnell pers. comm.). Elsewhere in south-east Brazil, it was reported that subsurface paleotopography, rather than surface topography, was the controlling influence on spatial and temporal developments of saturated zones (Cosandey & de Oliveira 1996). Thus some caution in accepting topographic indices *per se* is required when dealing with the deeply weathered regoliths of the humid tropics. Moreover, the poor correlation between measured soil saturation and the topographic indices in a few studies may be due in part to the bedrock topography issue (Beven *et al.* 1995, Bonell 1998b).

Elsewhere there has been recognition that TOPMODEL predictions of topographic indices, as well as depth to the water table and estimated transmissivities, are highly sensitive to the incorporated DEM map scale and contour resolution (Wolock & Price 1994). Further field validation to determine the optimal map scale and contour resolution is required. Similar comments apply to the sensitivity of transmissivity (or field saturated hydraulic conductivity) to DEM scale and contour resolution. A large transmissivity might be compensating for overestimates in ln $(a/\tan\beta)$ caused by the upslope drainage area, a, not extending to the drainage divide as assumed in TOPMODEL; instead the actual contribution area could be more spatially discontinuous.

Linked with high transmissivity estimates, is also the role of macropores which are able to transmit higher volumes of percolation (known as preferential flow which bypass the soil matrix) to the water table in saturated, deep tropical moist soils compared with humid temperate forests (Molicova *et al.* 1997, Bonell 1998b). Such phenomena create transient saturated zones of a more complex structure than assumed in TOPMODEL, and do not meet the mathematical, exponential assumption describing the decline in saturated hydraulic conductivity with depth.

Field testing of catchment soil moisture patterns under the temperate climate

The topohydrological models offer the theoretical capacity of representing the evolution of soil moisture status in time over a catchment. Such predictions of soil moisture however remain still conceptual when compared with practical needs, such as ground truthing of remotely sensed measurements, establishing of catchment wide-antecedent conditions for runoff and drought simulations, and decision making according to landuse conversion scenarios. In a 1.3 km^2 catchment in Brittany, the use of purely topographic considerations were inadequate for near surface soil moisture (0.05 m depth) (Crave & Gascuel-Odoux 1997). This means that the distribution of water content in space and time was not wholly controlled by topography. Moreover the existence of contrasts in physical soil properties further weakens the influence of topography. The authors determined an upper slope domain where water content was nearly constant and varied slowly and also a lower slope domain where soil moisture status increased and was highly variable. The two domains were most closely associated with spatial distribution of contrasting soil physical properties. Since near-surface soil moisture conditions are also a determinant of successful tree replanting, the observations of Crave and Gascuel-Odoux (1997) are highly relevant and need replication in the humid tropics.

With respect to the identification of soil moisture patterns over a catchment in terms of soil profiles with a strong potential of saturation, and of those subject to waterlogging, Grayson and Western (1998) proposed an analysis which can be easily conducted in the field. These authors used the concept of time stability of soil moisture patterns applied to catchments with significant relief (Vachaud *et al.* 1985). Time stability of soil moisture can be considered as temporal persistance of a spatial pattern. Vachaud *et al.* (1985) showed that particular sites in the field always displayed relative mean behaviour while others always displayed extreme values. When the relative moisture values of all sites were ranked, certain sites showed the same relative wetness, i.e. the temporal fluctuations of those particular sites were the same as that of the field average. Underlying this concept is an assumption of a linear relationship between soil water storage at successive measurement times across all spatial locations (Kachanovski & de Jong 1988). This concept obeys the same logic for soil moisture redistribution as that of topographic (wetness) index.

Grayson *et al.* (1997) applied the above considerations in duplex soils with pasture cover in temperate regions in the 10.5 ha Tarrawarra catchment, Australia. They showed that soil moisture patterns in these duplex soils (clay loam/clay texture) displayed quite different spatial properties in dry summer periods compared with wet winter periods. In summer, the variation across the landscape was apparently random because the hillslope hydrology was influenced by vertical fluxes through rapid evaporation, thus preventing lateral moisture redistribution. By contrast, in the wetter winter periods there was a high level of organisation associated with topographic effects with those areas of high convergence being wetter than planar or divergent areas due to surface and subsurface lateral flow processes (Western *et al.* 1999). Grayson *et al.* (1977) proposed that the spatial distribution of soil moisture occurred in two "preferred" states with a transition of one or two months, based on the analysis of data from other global experimental sites in the temperate regions. The "switch" is described in terms of dominance of lateral over vertical water fluxes. The lateral fluxes are topographically driven (not locally controlled) while the vertical fluxes obey local controls in terms of evapotranspiration and soil properties. It is important to note, however, that the Tarrawarra project focused only on the top 0.30 m of soil (shallow in comparison to humid tropic soils), which was the most hydrologically active in the runoff process in these duplex soils (Western *et al.* 1999).

Grayson *et al.* (1997) did extend their analysis using a daily rainfall-runoff model (MODHYDROLOG) to define relative soil wetness in basins of other climatic regions of Australia to assess whether the same spatial "switching behaviour" also occurs between two preferred soil moisture states. These other basins, however, like the Tarrawarra, were characterised by duplex soils where a heavy clay soil subhorizon underlies a lighter, textural topsoil, thus, making such topsoils the most hydrologically active. Grayson *et al.* (1997) inferred from MODHYDROLOG the continued existence of lateral flow-dominated in comparison with vertical flow-dominated patterns in these other basins; the persistence of either preferred state and the duration of transition between the two were strongly dependent on seasonality of rainfall and potential evapotranspiration. Nonetheless, this work pointed towards the prospective need for two separate soil wetness indices representing the corresponding non-local- (lateral flux) and local- (vertical flux) preferred states, especially if the "switching" between these states is short in duration.

Subsequently, Grayson and Western (1998) investigated whether there were other sites which exhibited steady mean or steady extreme behaviour over time in catchments with significant relief. The corresponding data sets covered multiple seasons and the sampling intervals were not related to precipitation events. Thus the sampling was essentially random in respect to precipitation. The authors found that in spite of general inconsistency of spatial moisture field over time, there were some specific locations within the landscape which exhibited time-stable behaviour. In addition, they observed that some of the time-stable behaviour sites could be considered representative of the areal mean soil moisture. Such properties are to be linked with systematically the same moisture footprint as the statistically derived average of the spatial moisture field composed of point measurements. Therefore, suitable locations could be used for the direct monitoring of the mean areal response. Grayson and Western (1998) called these locations "Catchment Average Soil Moisture Monitoring (CASMM) sites". One of the objectives of this research was to assess whether the location of these sites could be *a priori* predictable in terms of topography, soil texture and vegetation cover. In this respect the authors call for further investigations elsewhere which also apply to the humid tropics.

The CASMM sites offer an experimental alternative approach to acquire ground truthing for the purpose of remote sensing and flood and drought forecasting by their ability to provide areal average estimation of soil water content. This method provides a simple reliable way of "gauging" soil moisture regimes and deriving a sampling strategy for monitoring of soil moisture status using minimum point measurements. In respect to forestation strategies based on the topographic-wetness index, this approach can contribute to securing primary knowledge on the organisation and the stability of soil moisture patterns, and should precede a modelling effort. Furthermore, in deriving the soil moisture pattern by direct measurements it can replace the topohydrological modelling framework which, in terms of topographic-wetness attributes, provides only an indicator of the soil moisture pattern. Even if the assumptions underlying the physically-based modelling hold more precise for a selected environment, modelling outputs could never be "better" than direct measurements. The attraction of modelling techniques remains their capacity to extrapolate data and in the case of topographic-wetness models, a possible overlay with other water and mass related fluxes (Vachaud *et al.* 1985, Grayson & Western 1998).

Moreover, in line with their field key findings Western *et al.* (1999) adapted the modelling framework of THALES (Moore & Grayson 1991) in order to set up a process-related hydrological modelling of the Tarrawarra catchment. Modifications to THALES were made to include saturation overland flow, subsurface stormflow within the A soil horizon (defined in Chorley 1978), changes in soil moisture storage of the B horizon and evapotranspiration. With limited calibration effort, THALES was able to broadly simulate the seasonal changes in the characteristics of the spatial soil moisture patterns (including the "switch" between the two contrasting seasonal types). The principal differences were that the simulated soil moisture patterns were much smoother than the observed patterns. Detailed examination of the errors (residuals) in the spatial occurrence of soil moisture, simulated by THALES, suggested however that there was a need for further structural modifications within this model. For example, potential evapotranspiration appeared to be spatially variable (not uniform as assumed) due to differences in topographical aspect linked with variations in receipt of solar radiation. In addition, a modification of the subsurface, lateral redistribution process description would be needed to include unsaturated, redistribution of soil moisture.

The introduction of the above two modifications would better partition the lateral (unsaturated soil moisture redistribution) fluxes from the vertical fluxes of evapotranspiration. Such partitioning is critical during dry periods to better define the spatial "random" patterns within soil moisture field. The same knowledge is also critical to guide forestation strategies.

Field testing of catchment soil moisture patterns in humid tropics

Whether such preferred states as described above are also appropriate to more deeply, weathered profiles of the humid tropics still requires investigation. A compounding (and unknown) issue is the degree to which unsaturated zone is coupled to saturated zone and the ability of tree roots to access groundwater in these deeply weathered profiles. Research in French Guyana (Molicova *et al.* 1997) and in Peru (Vertessy & Elsenbeer 1999) focused only on the rainy seasons so that there was no verification on spatial soil moisture patterns during dry, hot periods associated with strong evaporation.

It is pertinent at this point, however, to outline early results of soils moisture patterns reported from MARVEX because they do not conform to the previous description for Australian catchments, and also emphasise the need for caution in extrapolation of the latter work to the humid tropics. The Mahurangi basin is characterised by a warm, humid temperate climate (verging on subtropical). Moreover, whilst the soils remain relatively shallow (ca. 1 m in depth, over sandstones and siltstones): these clay loams do not have the marked contrast in permeability like duplex soils, and thus are more in line with humid tropic regoliths. Through the use of a dense network of soil moisture monitoring systems, Woods *et al.* (2001) show that there is little correlation between soil moisture and topographic position (non-local controls) in the top 0.3 m depth from intensive sampling campaigns covering extremely wet to relatively dry conditions. Significantly, data from deeper instruments (ca. 1.5 m in depth) appear to confirm this observation. Woods *et al.* (2001), observed that the apparent lack of topographic influences during wetter periods reported by Grayson *et al.* (1997) need further exploration. Other possibilities that need consideration could be the hydrological response being controlled by deeper groundwater processes or the lateral processes on hillslopes being more influenced by preferred flow pathways in macropores (Woods *et al.* 2001).

The importance of deeper groundwater was highlighted earlier in association with the more deeply weathered regoliths of the humid tropics. For example, from modelling hydrometric-environmental isotope data during storm events, Barnes and Bonell (1996) suggested that a large groundwater store in excess of 3000 mm of rain equivalent capacity underlay tropical rain forest in a north-east Queensland study. This deep groundwater body then sustains the rain forest transpiration demands during the following dry season (Bonell *et al.* 1998). In the Western Ghats of India, the evergreen forests experience in excess of 4000 mm of rain over a short summer season (June–September) and then have the ability to cope thereafter with even a longer dry season (six months or more). These evergreen forests have impressive tap roots which must extend through the deeply weathered, but friable soil profiles to deep groundwater to sustain these forests. This led Bonell (1998a) to put forward the hypothesis that a significant proportion of closed tropical forests (but not all) was coupled through their tap root system to unconfined groundwater. Moreover, the high infiltration and percolation rates that these forest soils engendered provide a basis for high recharge to groundwater for its maintenance. Nepstad *et al.* (1994), in a study in south-east Amazonia, Brazil, provided some support for this hypothesis. They measured root systems extending deeper than 18 m which were capable of accessing deeper soil moisture and groundwater to maintain transpiration demands during dry seasons for up to five months. Elsewhere, a study of hillslope hydrology in Brunei tropical forest by Dykes and Thornes (2000) established that the bulk of subsurface lateral flow occurred mostly at the soil-bed rock interface (up to 10 m in depth).

The existing generation of topographic-wetness models are not coupled with deeper groundwater to cater for the ability of tropical forest species to access deeper moisture which in the longer term becomes an important consideration in forestation. Unfortunately, our knowledge of the groundwater hydrology over extensive areas of the humid tropics is limited (Foster 1993, Foster & Chilton 1993, Foster *et al.* 2002). Similarly, we have little data on the rooting characteristics of forests linked with their ability to extract deeper subsurface moisture (Bonell 1999).

Example of testing of topographic-wetness models in humid tropics

Research by Molicova *et al.* (1997) and Vertessy and Elsenbeer (1999) provide some insight into the complexity of the spatial and temporal organisation of soil moisture during storms which could have implications for soil water redistribution during the post-storm period. The two "preferred state" patterns of spatial soil moisture organisation described by Grayson *et al.* (1997) under temperate climatic conditions are not yet verified in the humid tropics because the works by Molicova *et al.* (1997) and Vertessy and Elsenbeer (1999) were undertaken during the wet seasons, i.e. where the spatial soil moisture pattern obeys the topographic logic. The spatial organisation of soil moisture under dry season conditions still remains to be determined. Some inconsistencies between the theoretical soil moisture distribution with field measurements were shown even during the wet season. Molicova *et al.* (1997), for example, showed a complex development of perched water tables along a slope transect in a small catchment (1.5 ha) in French Guyana. At some points, saturation extended downwards from the surface whereas at other sites saturation first developed in soil horizons from below and then extended upwards towards the surface. Moreover, the classical concept of the development of saturation zones first at the base of slope and then extending progressively upslope, assumed in the framework of the variable source-area concept (Hewlett & Hibbert 1967), was not supported in the study of Molicova *et al.* (1997).

Elsewhere one of the principal criticisms of spatial hydrological models is that the "good" model simulations of storm hydrographs do not imply a realistic representation of within catchment (pixel) soil moisture and runoff dynamics (Grayson *et al.* 1992). Outside the humid temperature latitudes (e.g. Grayson *et al.* 1997, Western *et al.* 1999), the work of Vertessy and Elsenbeer (1999) is the only one so far in the humid tropics that compare field observations of overland flow occurrence with the internal predictions of a spatial hydrological model, i.e. TOPOG-SBM, in a small (~ 0.75 ha) catchment in Peru. One of the model sets (K_{sat} values pooled in a single catchment population, random allocation of cumulative frequency of log-transformed values across the whole catchment) generated the closest physically, realistic pattern of overland flow generation. However, a major obstacle to Vertessy and Elsenbeer (1999) having more success in their simulations is probably their inability to represent the rapid transfer of subsurface stormflow by pipes both spatially and volumetrically in the absence of this information. In fact pipeflow is a critical component in stormflow generation because its paramount role in rapid water redistribution can result in a different pattern than the one predicted by topographic-wetness analysis.

Further, Molicova (1998) set up a new modelling framework coupling the hydrological and hydrochemical fluxes (chloride, potassium). The model was developed using the process end-members (Hooper *et al.* 1990), namely, perched water table, recharge soil component and overland flow. Unlike in the geochemical approach, chemical signatures of these end-members were linked to the runoff generation processes rather than to the depths of their origin (Robson & Neal 1990, Robson *et al.* 1992). This study intended to address the need for reconciling field results from a combined hydrological-geochemical approach (Bonell & Fritsch 1997). Moreover, a combined approach will enable the identification of upslope sources, the contribution of which were ignored by previous research in terms of sustaining moisture content and nutrient redistribution during prolonged rainless periods. The use of hydrochemical data could reveal the role of water- borne transport and redistribution which are highly relevant to forestation strategies (Ball & Trudgill 1997).

Role of forestation of degraded land within the context of a controversial hydrological issue

In the humid tropics considerable publicity has focused on the linkage between increased flooding and decreased dry weather flow arising from forest removal. Such publicity is contrary to findings from existing limited number of controlled experimental catchments in the humid tropics using the "classical" paired catchment approach (Hewlett *et al.* 1969). This method converts one of the forested drainage basins after a period of calibration while the undisturbed catchment acts as a "control" to estimate the impacts of the conversion on the hydrology. The general conclusion from these controlled experiments is that the most significant increases in the streamflow regime are connected with the "dry weather" or "delayed flow" component and not with the stormflow or "quickflow" component. Such changes are due principally to savings from transpiration via the removal of deeper rooted trees (Bonell & Balek 1993).

However popular reports of the linkage between increased flooding arising from deforestation coupled with a converse decrease in dry weather flows have persisted. Identified with this linkage was the commonly stated belief that forests act as "sponges" so that subsequent conversion increases floods. The common reaction in the 1980s was to reject such unsubstantiated claims and myths in the absence of rigorous scientific evidence (e.g. Hamilton & King 1983, Hamilton 1990). The notion of forests acting as infinite sponges has been disproved because floods can also emanate from forest as storm events increase in intensity and duration (Pereira 1991, Bonell & Balek 1993).

On the other hand, in selected, highly degraded landscapes some scientific credibility may be attached to the described effects on dry season streamflow. The existing controlled experiments did not involve immediate soil degradation because in most cases a replacement cover crop provided soil protection (Bruijnzeel 1989). In contrast, degraded agricultural landscapes, many originating from previously converted forest long ago, are quite extensive and typical of the tropics. Within such secondary landuse cover, the permeability of soil has markedly declined due to the long period of manipulation by agriculture and animal husbandry. Surface infiltration rates are more likely reduced through dispersion and sealing by heavy rain (Bruijnzeel 1989, Pereira 1991). These reduced rates are further accentuated by trampling and compaction by livestock, which increase infiltration-excess overland flow during rainy periods. In these conditions water is lost for deep percolation which reduces dry weather streamflow from a depleted groundwater storage. Forestation in the mid term should help increase surface infiltration and encourage deep percolation, and, therefore enhance groundwater recharge. The latter could cause dry weather streamflow to be more sustained. In the short term, however, forestation might have a negative effect by reducing even further what limited soil moisture reserves are available through increased transpiration, and thus diminish, opportunities for percolation to groundwater even more. Ultimately, whether delayed flow recovers or not depends on the changes in the overall catchment water balance, notably within total evaporation ("dry canopy" transpiration and "wet canopy" evaporation) of components, in comparison with percolation to groundwater (Scott *et al.*, pers. comm.). Should the evaporation component be higher in quantity than groundwater recharge (percolation) then forestation will have an adverse (negative) effect on dry weather flow.

Recently, based on a study in Tanzania, Sandström (1995) has provided support for the above hypotheses. The most vulnerable areas to deforestation were steep slopes which consisted of fine textured soils that enhanced infiltration-excess overland flow during storms. Further, deep percolation was reduced because of the loss of macropores (associated the forest roots) by the development of surface soil crusts (scaling) from raindrop compaction and trampling from overgrazing. The latter induced erosion and land degradation from the enhanced occurrence of infiltration-excess overland flow (Sandström 1995). This work was reviewed in more detail elsewhere (Bonell 1998a).

Elsewhere the UNESCO International Hydrological Programme (IHP), in collaboration with the Karnataka Forest Department and the National Institute of Hydrology (Belgaum), have established a preliminary study in the Western Ghats to evaluate the impact of various forestation strategies on the landuse hydrology within the semi-evergreen and deciduous forests and adjacent degraded landscapes. The experimental strategy followed (UNESCO 1997) is similar to that described by Gilmour *et al.* (1987) in Nepal whereby the determination of *in situ* soil hydraulic properties across spectrum soils, forestation strategies and different states of degraded land are were linked with short- term rainfall intensities. In this way the most appropriate hypotheses can be established in preparation for a multiple, controlled drainage basin experiments or second stage "paired catchment" approach. This second stage is a reverse of the traditional "calibrate, cut and publish" approach (Hibbert 1967, Hewlett *et al.* 1969, Bosch & Hewlett 1982) in favour of studying long-term hydrological response to forestation and rehabilitation of existing degraded landscapes.

Conclusions

Topographic-wetness models provide a spatial framework for selecting the most appropriate tree species for replanting based on their most optimal requirements in terms of the local hydrology and especially tolerance to drought. While these spatial models are not perfect especially in connection with predicting storm runoff, it is believed that in the context of hydrology, the spatial organisation of tree species is more likely influenced by transpiration requirements linked with the redistribution of soil moisture and position of the water table in-between storms rather than the spatial and temporal occurrences of storm runoff. Under these conditions, there is sufficient evidence that these topographic-wetness models have promising potential, but more field testing is required for application in forestation. In that regard, greater attention needs to be directed towards correlating either the TOPMODEL topographic index, or TOPOG wetness index with the physiological characteristics of various tree species coupled with different replanting strategies.

Parallel studies in the humid tropics, based on similar lines to those undertaken in temperate south-east Australia and New Zealand (Grayson *et al.* 1997, Grayson & Western 1998, Western *et al.* 1999, Woods *et al.* 2001) are needed to verify spatial and temporal organisations of soil moisture. Especially pertinent to the development of a forestation strategy, i.e. tree species selection linked with optimal soil moisture requirements, is to determine whether there are similar seasonal "preferred" states of soil moisture, and under what environmental conditions such "preferred" states are prevalent. In the absence of a shallow impeding horizon of much lower permeability compared with duplex soils, the spatial and temporal organisations of surficial soil moisture may be more random and locally controlled (Woods *et al.* 2001). Elsewhere, Crave and Gascuel-Odoux (1997) emphasised the more dominant role of contrasting soil physical properties (i.e. different soil types and associated hydraulic properties) in influencing the spatial distribution of surficial soil moisture (ca. 0.05 m in depth), especially in low relief environments. In these circumstances, a different forestation strategy may have to be considered with the use of pioneer crop species. The selection of this species is based more on the spatial organisation of soil physical properties (i.e. based on a good soil map) coupled with good knowledge of the corresponding soil hydraulic properties (e.g. the soil moisture characteristic, unsaturated hydraulic conductivity) linked with soil moisture retention. Subsequently, tree growth (in terms of the local hydrology) may be more controlled by deeper, subsurface lateral seepage (e.g. Dykes & Thornes 2000) or groundwater whose spatial organisation may exert a greater non-local control on the lines described by Grayson *et al.* (1997). In the longer term, improved *a priori* knowledge of the hillslope hydrology of different humid tropic environment will enable the described spatial models to be modified to incorporate such considerations as the soil-bedrock topography. This in turn will have greater application in restoration community ecology.

There are, however, practical obstacles in terms of the field testing and adaptation of spatial topographic-wetness models. Due to the "shallow" nature of the most active hydrological layer of duplex soils, Grayson *et al.* (1997) were able to make relatively rapid and frequent soil measurements in the top 0.3-m layer over time using an all-terrain vehicle, incorporating a differential global positioning system, the hydraulic insertion of TDR (time domain reflectometry) probes and automatic logging of data (approximately 500 individual measurements on each occasion) (Western *et al.* 1999). This methodology is not practical when there is a need for monitoring of soil moisture in more deeply, weathered humid tropic soils of several metres deep. The same method is also impractical for use in tropical forests. Conventional alternative methodologies, well-known in hydrology, but which are more time consuming will continue to be of relevance here (e.g. Bonell *et al.* 1998, Woods *et al.* 2001). In this context, the foregoing discussion has highlighted the need for a better understanding of unsaturated-saturated zone coupling linked with tree root characteristics at much greater depths, especially at the soil-weathered bedrock interface where saturated, lateral subsurface flow might occur. Moreover, there is a need for more multidisciplinary approach in hillslope hydrology (Bonell & Fritsch 1997) such as a combined hydrometric-hydrochemistry-modelling framework (Molicova 1998). The latter could also be pertinent for forestation strategies in terms of the spatial organisation of soil nutrients linked with water-borne transport within hillslopes.

Despite the concentrated effort within a few paired catchment studies in the humid tropics, a long-term hydrological study of the impacts of forestation and rehabilitation of degraded land is lacking (Bonell 1993). No comprehensive information at even a small drainage basin scale (≤ 10 km^2) addresses the basic hydrological questions surrounding the controversial issue of increased flooding and, conversely, decreased low flows. Also not dealt with is the time span for hydrological recovery, where at some point water balance begins to resemble pre-disturbed forest conditions. The latter question is closely integrated with parallel questions connected with aspects of biogeochemical cycling (and related balances) as well as various pedogenic processes. Water is the prime transporting agent within the earth sciences and within biogeochemical cycling in particular. Consequently, a multi-disciplinary approach is mandatory when considering restoration ecology.

This review has highlighted the urgent need for the establishment of long-term controlled experimental catchments which would provide an integrated, multi-disciplinary framework for evaluating the impacts of forestation of degraded land on the hydrology and related systematic studies. In other words, the traditional paired catchment approach focusing on the hydrological impacts of forest conversion needs to be reversed (Bonell 1993). The socio-economics of the humid tropics causing an expansion in degraded land, coupled with increasing pressure on the dwindling forest resources, is also dictating the need for the above new experimental strategy. In this context, the UNESCO IHP project within Karnataka India, is one of the few studies as a first step towards achieving this goal (UNESCO 1997).

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