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Development of the *for*SIM model to quantify positive and negative hydrological impacts of tropical reforestation

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Abstract

Existing approaches to modelling the impacts of reforestation on tropical hydrology only simulate one or two changes, thereby limiting our ability to quantify the balance between complex positive and negative changes, even for a single micro-basin. To initiate a more holistic and multi-scale approach, we develop a new simulation model structure within the Matlab-Simulink systems environment that firstly, illustrates quantifiable interrelationships between reforestation-related hydrological changes in the component systems of evapotranspiration, runoff generation, sediment delivery and nutrient processes. Secondly, the model structure allows us to highlight basin-scale time-series observations needed to quantify reforestation-related changes in the component hydrological processes.

The dynamic model developed is called *for*SIM and comprises of component models that are derived by means of the data-based mechanistic (DBM) philosophy. Such a modelling approach is required to constrain the large uncertainties that can arise from whole system modelling. The review of the hydrological processes and controlling characteristics that change following reforestation and, therefore, need to be simulated, has highlighted the lack of basin-scale time-series observations of the potentially positive impacts of ‘protective’ reforestation on sediment and nutrient delivery, and the need to utilise more macro-scale data. The next phase of the modelling process is to derive estimates of systems parameters and simulation scenarios for specific macro-basins in the tropics undergoing extensive reforestation.

Keywords: Hydrology; Plantation; Reforestation; Systems model; Transfer function; Tropical forestry

1. Introduction

Reforestation is the establishment of plantations within areas formerly converted from forestland: United Nations Framework Convention and Climate Change (2002). The negative impact of reforestation on water availability in tropical rivers is well publicised in recent literature (e.g., Calder, 2004, 2006; Hayward, 2005) and has considerable support from experimental basin studies within the tropics (Bruijnzeel, 1990, 2001, 2004). This negative impact does, however: (a) need to be put in the context of uncertainties arising from the interpretation of short-term, micro-basin data and (b) need to be judged against quantified positive impacts of reforestation. This balancing of the positive and negative hydrological impacts of tropical reforestation has not been undertaken within a single simulation model, possibly because of three reasons. First, there is a dearth of certain hydrological time-series data for the tropics (Wood, 2002; Bonell, 2004; Scott et al., 2004; Chappell and Sherlock, 2005). Secondly, a numerical structure to illustrate *all* of the hydrological impacts that might be dominant within a particular tropical region has not been devised. Thirdly, there is now an appreciation of the large predictive uncertainties that arise from the use of complex numerical models (Beven, 2001a,b). Additionally, there is an appreciation that such models should incorporate all those hydrological processes that dominate at different scales, from micro-basins ($<50\ km^2$) to macro-basins ($>1000\ km^2$). For example, channel routing of riverflow is not a major control on response at the small scale, but becomes critical at the macro-basin scale. Those impacts said to be largely hydrological, cover changes to the volume and timing of riverflow and evapotranspiration, plus changes to sediment delivery and river water quality via changes to soil, soil–water and water within rocks (Roberts, 2000; Evans and Turnbull, 2004; Scott et al., 2004).

This study has two aims. Firstly, we aim to develop a model structure, which would allow quantitative comparison of hydrological changes resulting from reforestation that might be dominant within a particular tropical region. Secondly, we

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aim to highlight forest-related and hydrological variables (i.e., time-series) and model parameters that need to be quantified more fully to allow realistic assessment of the balance between the positive and negative impacts of dominant hydrological changes arising from tropical forestation. This is explicitly a pilot study highlighting missing data and providing a preliminary structure for ongoing and future field- and modelling-work. We first define the modelling approach, second, the controls on the hydrological processes; third, the links between the different processes (e.g., how output from the water-flow simulations can be used as input to the nutrient-flux simulations) and lastly, we consider the availability of data to allow future parameterisation of the component models.

2. Systems methodology

Our methodology seeks to combine all hydrological impacts accompanying reforestation at specific tropical locations within a single simulation model. Uncertainty in model simulation can increase dramatically with increasing numbers of model elements and parameters, to a point where simulation results become meaningless (Beven, 2001b). Consequently, we need to constrain the complexity of our model to produce uncertainty bands on the predictions small enough to make the simulations meaningful. This means that we need to identify only the *dominant modes* of the hydrological behaviour contained within observations at a required scale, using the least number of model elements and parameters (Young, 1999). Such models are said to be 'parsimonious' (after Tukey, 1961; Box and Jenkins, 1970). One such parsimonious modelling approach is the data-based mechanistic (DBM) approach of Young (1984, 2001). This is a type of *systems approach* where the dynamics of the state variable, e.g., riverflow without any errors in the field measurements, are represented by:

$$x(t_k) = f[x(t_{k-1}), u, \alpha; t_{k-1}] + \xi(t_k) \tag{1}$$

With observations of the state of the system (e.g., relationship between the true riverflow [without errors in the field measurements] and observed riverflow) sampled discretely in time, we also have:

$$y(t_k) = h[x, \beta; t_k] + \eta(t_k) \tag{2}$$

where x is the vector of state variables, including field measurement errors, u a vector of measured input drivers (such as rainfall and root growth), y a vector of output responses (e.g., true riverflow), α a vector of the system model parameters (e.g., recession constants describing water pathways), β a vector of parameters which relate the true variable (e.g., riverflow) to that measured, ξ a vector of the state variable dynamics that are not observable (i.e., the system noise), η a vector of (output) measurement errors, f and h vectors of linear or non-linear functions, t continuous time and t_k is the kth discrete instant in time (modified from Beck et al., 1993). One of the most commonly used functions (h) relating the vector of an input variable (u, e.g., rainfall) to the vector of an output response (y, e.g., overland flow) is the discrete-time, transfer function; and it can be given as:

$$\begin{cases} x(t_k) = \left[\dfrac{P}{1 - \Re z^{-1}} u(t_k - \delta)\right] \\ y(t_k) = x(t_k) + \eta(t_k) \end{cases} \tag{3}$$

which can be shown in explicit difference equation form as:

$$\begin{cases} x(t_k) = \Re x(t_{k-1}) + Pu(t_k - \delta) \\ y(t_k) = x(t_k) + \eta(t_k) \end{cases} \tag{4}$$

where P is the model production parameter, $\Re$ the recession term, δ the pure time delay between the input and initial output response, z^{-1} the backward shift operator (i.e., $z^{-m}u(t_k) = u(t_{k-m})$) and m is the number of backward shifts. The model parameters P and $\Re$ are then often used to derive the two dynamic response characteristics (DRCs: Post and Jakeman, 1996) of:

$$\mathrm{ssP} = \frac{P}{1 - \Re} \tag{5}$$

$$\mathrm{TC} = \frac{-t_{\mathrm{base}}}{\log_e(-\Re)} \tag{6}$$

where ssP is the steady state production (a 'mass-balance' term, e.g., runoff coefficient between rainfall and runoff), TC the time constant of the system (a 'residence time': Young, 2001) and t_{base} is the time base of the sampling (e.g., 1 h). Where different forestry case studies are available, changes to these DRCs of ssP and TC can be used to simulate changes in a hydrological system due to reforestation (or alternatively, forest loss: Post and Jakeman, 1996; Chappell et al., 2004b, 2006).

DBM modelling is one such systems approach identifying model structures and parameters incorporating transfer functions. The strength of the DBM method leading to its use in this instance is two-fold. First, many systems models use least squares (LS) algorithms to find or calibrate model parameters. The problem with these LS methods in transfer function estimation is that the noise within time-series data gives rise to considerable bias and uncertainty in the model parameters (Young, 1984). Within the DBM approach, model structure and parameter values are identified (or calibrated) by the simplified recursive instrument variable (SRIV) algorithm. In the SRIV approach, time-series data are pre-filtered using an estimate of a dynamic recession filter (Young, 1985) after an initial LS estimate. This removes higher frequency observational disturbances focusing the signal in the useful frequency range where dominant dynamic modes of the system are contained. Following this initial step, the instrumental variable method with specially generated 'mathematical instruments' is used, which removes the bias of the estimates. Both of these steps considerably reduce parametric uncertainty (Young, 1984, 1985).

The second advantage of DBM over other systems methods comes from its use of the objective statistical measure of the Young information criterion or YIC in the model and parameter identification/calibration:

$$\mathrm{YIC} = \log_e \frac{\sigma^2_{\mathrm{error}}}{\sigma^2_{\mathrm{obs}}} + \log_e\{\mathrm{NEVN}\} \quad (7)$$

The first term of YIC is a measure of the model efficiency, where $\sigma^2_{\mathrm{error}}$ is the variance in the model residuals and σ^2_{obs} is the variance in the observed output data (e.g., streamflow), and the second term NEVN (normalised error variance norm) is a measure of the degree of over-parameterisation (Young, 1985). Generally, as model complexity increases, so does the ability to capture more and more of dynamics in the observed time-series, but at the expense of growing parametric uncertainty. There is, therefore, an optimum complexity (or 'model order') given that more complexity increases the uncertainty in the individual parameters identified. The YIC is an indicator of whether the model has become over complex (i.e., too many parameters) given the amount of information contained within the observed output time-series. As a result, we consider that the DBM approach to modelling does not give more complex structures of hydrological processes than is justified by the observations, as can be the case with physics-based and conceptual models, which require definition of component model structures prior to any modelling (Beven, 2001c). Within the DBM philosophy, *the perceptual model of the hydrological system under study is not defined before the simulations and, thereby, not limited by unjustified complexity.* The consequence of defining the most simple structure justified and using a method which implicitly derives uncertainty estimates, DBM techniques identify parameters (and DRCs) of the hydrological processes that have well defined values with quantified, small uncertainties. This means that reforestation-related changes in hydrological systems are more likely to be seen above the uncertainties due to errors in the observations and model.

3. Identifying DBM hydrological models

3.1. Defining component models and drivers

The first stage within our modelling strategy is to consider how forest stands change, as plantations are established, and then mature. These changes to the canopy structure, roots and soils are parameterised within our model because they regulate hydrological behaviour. For example, root development, a 'forest change', affects the potential for both water abstraction and slope stabilisation—'hydrological changes' (Sidle and Wu, 1999; Roberts, 2000). Drainage basin hydrological systems can be very dynamic from time-scales of minutes in the case of small streams responding to tropical rainfall (Chappell et al., 1999a) to years where strong El Niño Southern Oscillation (ENSO) cycles are present in tropical rainfall (Boochabun et al., 2004). Thus, the second stage is the identification of the dominant hydrological drivers or inputs of precipitation and energy. Thirdly, if the hydrological responses to plantation development are known to include changes to runoff pathways, evaporation, flow regime of rivers, sediment delivery and nutrient flux (Bruijnzeel, 2004; Roberts, 2000; Evans and Turnbull, 2004), we need to consider how all these processes might be described within a parsimonious model. Within the following analysis, we consider: (i) the dominant forest- and water-related controls on key hydrological outputs and (ii) existing applications of DBM approaches using transfer functions sometimes combined with non-linear filters.

3.2. Time-dependent reforestation drivers

Model simulations start by the user inputting the proportion of the drainage basin (micro-, meso- or macro-scale) being simulated that is planted with trees. As each tree grows, its canopy, root network and biochemical inputs to the soil all increase and can be simulated as four key processes:

(1) As a tree canopy expands, its leaf mass increases; sometimes in a linear manner (Kittredge, 1948, p. 32). The leaf mass, like the Leaf Area Index (LAI), is a key regulator of the hydrological pathways of wet-canopy evaporation (Deguchi et al., 2006) and transpiration (Granier et al., 1992; Wu et al., 1997).
(2) As rooting density and depth increases, trees have a greater capacity to abstract soil moisture so that transpiration increases (Roberts et al., 2004; Tanaka et al., 2004). Equally, development of the root network increases the shear strength of the regolith (O'Loughlin and Watson, 1979; Sidle, 1991), thereby, reducing the potential for slope instability and hence sediment delivery to rivers (Burton and Bathurst, 1998).
(3) As the canopy and roots develop, each tree increasingly adds organic matter and chemicals to the soil. For many tree species, these exudates are beneficial to the soil structure and nutrient status-cum-fertility of the soil (Innes et al., 2004; Scott et al., 2004). However, some trees have exudates that can negatively affect the soil structure under certain circumstances (Herbuts and de Buyl, 1981; Nys and Ranger, 1985).
(4) Reforestation of slopes previously used for arable agriculture, often indirectly reduces the inputs of artificial chemicals, notably pesticides and inorganic fertilizers, which improves the microbiological status of soils (Yusoff et al., 2001; McClain, 2004; Geissen and Guzman, 2006) and, thereby, the soil structural development (Wendling et al., 2005) and nutrient cycling processes (Holden and Fierer, 2005). Some reforestation schemes are, however, associated with artificial chemical additions (Morris, 2001) and these need to be quantified.

3.3. Time-dependent hydrological drivers

Within-storm changes in riverflow, nutrient and sediment flux within reforested areas of the tropics (Grip et al., 2004) is testament to the control of rainfall on these hydrological processes. Over several days, rainfall also strongly regulates tropical wet-canopy evaporation (Chappell et al., 2001; Kume et al., 2006). Within the seasonal tropics and semi-arid tropics, rainfall also moderates transpiration via changes to soil moisture status (Clark et al., 2004). Given that rainfall controls all of these hydrological processes, a rainfall time-series is the most important input hydrological variable. Given the role of energy, notably net radiation, in the regulation of transpiration and wet-canopy evaporation (Schulz and Jarvis, 2004), this is considered the second most important input hydrological variable.

3.4. DBM runoff pathways model

Existing examples of DBM models of tropical runoff pathways include one or more of the components of overland flow, lateral flow within soils and deeper subsurface flow within permeable regolith and rock (Young, 2001; Chappell et al., 2006). All of these models utilise linear transfer functions (Eq. (3)) between an effective rainfall times-series and a water-flow time-series measured on slopes or in channels.

Changing soil moisture conditions (and moisture deeper within the underlying regolith: Chappell et al., 2004b) make the relationships between rainfall and water-flow non-linear. This effect can be parameterised by combining the linear transfer function with a non-linear function. Non-linear functions commonly used within the DBM methodology, include the store-surrogate sub-model (SSSM), conditioned on the water-flow output, and the Bedford-Ouse sub-model (BOSM), which is independent of the water-flow output (Young, 2001). The IHACRES non-linear filter (e.g., Post and Jakeman, 1996) is based on the DBM-BOSM routine, but extended to incorporate the input of temperature dynamics. An example of an infiltration-excess overland flow model incorporating the BOSM non-linear filter and a linear transfer function is given in Fig. 1 (adapted from Chappell et al., 2006). Fawcett et al. (1997) went further with their DBM modelling by using rainfall

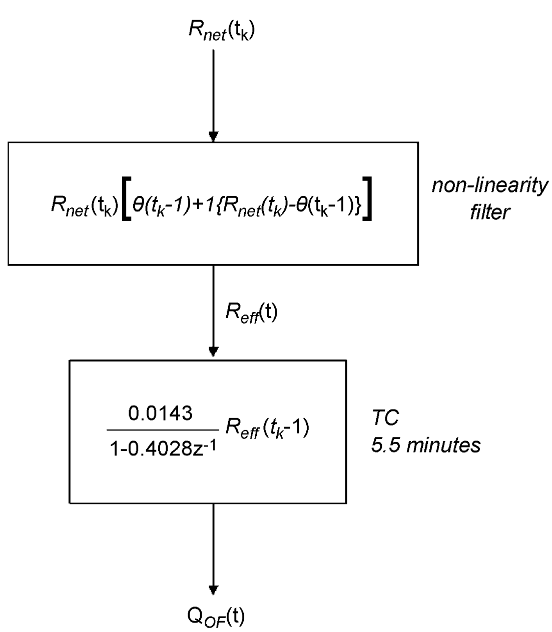

Fig. 1. A data-based mechanistic (DBM) model of infiltration-excess overland flow, where R_{net} is the net precipitation input and Q_{OF} is the infiltration-excess overland flow output (see Chappell et al., 2006).

to simulate soil moisture that was the used to estimate streamflow. Use of two DBM models *in series*, as in Fawcett et al. (1997), allows the soil moisture dynamics to be first simulated for subsequent input in to models of: (i) soil moisture regulation of transpiration (Roberts et al., 2004; Tanaka et al., 2004), (ii) slope instability (Collison and Anderson, 1996; Burton and Bathurst, 1998) and (iii) soil–water quality and nutrient status (Geissen and Guzman, 2006).

The presence of deeper water pathways within permeable regolith or permeable rock beneath the soil is often overlooked within the tropical environment (Bonell, 2004). Yet, some tropical regions are underlain by major rock aquifers, including fissured aquifers (Institute of Geography, 1999; Struckmeier and Richts, 2004) or tens of metres of permeable regolith (George, 1992; Bonell et al., 1998), for example, the weathered granite saprolite in Peninsular Malaysia (Zektser and Everett, 2004; Chappell et al., 2005, 2007). The presence of these deeper pathways firstly affects DBM parameters describing rainfall-streamflow response (Young, 2001). Secondly, if a significant proportion of subsurface percolation moves rapidly into these deeper layers, then this moisture would not be available to support transpiration (Pereira, 1959). Consequently, the differential impact of plantation trees compared to less deeply rooted vegetation could be less marked (Kirby et al., 1991, Table 35; Chappell and Bonell, 2005), however, there is a lack of studies in the tropics that have quantified hydrological budgets in drainage basins with such permeable regolith or rock.

3.5. DBM evapotranspiration model

Fewer DBM models of the evapotranspiration components of wet-canopy evaporation and transpiration have been identified. Chappell et al. (2006) identified a DBM transpiration model from the single input variable of rising-stage air temperature, and Schulz and Jarvis (2004) identified a combined transpiration and wet-canopy evaporation model by the DBM approach. Soil moisture regulates transpiration in the arid tropics (Clark et al., 2004) and dry season of the seasonal tropics (Tanaka et al., 2004). Thus, soil moisture in addition to net radiation or air temperature (Van Dijk et al., 2004) and the long-term dynamics of canopy mass (Granier et al., 1992; Wu et al., 1997) should be used to simulate transpiration.

DBM models of wet-canopy evaporation alone have not yet been identified. Chappell et al. (2004c) has, however, developed a conceptual model of wet-canopy evaporation, which adds the difference between gross and net rainfall at 5-min intervals to a canopy store, which depletes by evaporation according to a maximum 5-min rate set by the net radiation. They state that a DBM model will be developed once direct observations of canopy wetness are available from an ongoing experiment around Bukit Atur, Malaysian Borneo. Soil evaporation is lumped within the DBM model of Schulz and Jarvis (2004), but a separate DBM soil evaporation model has yet to be published.

The DBM evapotranspiration models discussed so far use time-series data from the small scales of plots to micro-basins

(<50 km^2). Similar DBM models of evapotranspiration processes are needed at the meso-scale (50–1000 km^2) and macro-scale (>1000 km^2), as it may be necessary to include the effects of macro-scale heterogeneity in vegetation and terrain. Indeed, simulation models show that large-scale heterogeneity in land-cover resulting from tropical deforestation may reduce regional rainfall through reductions in macro-scale evapotranspiration (Zeng et al., 1999; Roy et al., 2003; Werth and Avissar, 2004; Roy and Walsh, 2005). It is, therefore, plausible that large-scale reforestation could increase regional rainfall via changes to the macro-scale evapotranspiration.

3.6. DBM riverflow model

DBM modelling of runoff pathways has been used to model riverflow (or channel flow) by at least three ways. First, riverflow has been simulated using a 'first-order' or single water pathway (Chappell et al., 1999a). Secondly, riverflow has been simulated by identifying higher order models that can be decomposed into multiple water pathways (Young, 2001). Thirdly, riverflow has been simulated by combining separately identified DBM overland flow and subsurface flow models (Chappell et al., 2006). DBM modelling of flow pathway components of riverflow normally uses micro-basin data. A critical issue is one of understanding how these pathways, and hence model parameters, change with drainage basin size from the micro-basin to the macro-basin. With increasing scale, channel routing velocities become as important as subsurface routing velocities (Beven, 2001c), and greater contributions from deeper groundwater pathways can be seen (Chappell et al., 1999a). The resultant damping of response has been parameterised with an additional DBM transfer function that has a time-constant representing the channel routing effects (Lees et al., 1994). A model that simulates riverflow dynamics from micro- to macro-scales is critical to the simulation of sediment and nutrient delivery processes, which also change with spatial scale (Dietrich and Dunne, 1978; Douglas et al., 1999; Vorosmarty et al., 2003; Curtis et al., 2005; Boyer et al., 2006).

3.7. DBM sediment delivery model

The key controls on soil erosion at the soil surface are the erosivity and erodibility. The erosivity is controlled by the characteristics of the water pathways such as kinetic energy, water velocity and soil seepage forces (Bryan et al., 1998), while the soil erodibility relates to measures such as aggregate stability (Chappell et al., 1999b; Salako et al., 2001) and shear strength (Eyles, 1968; Morgan, 1995). Soil instability is affected by biochemical inputs from trees that change physiochemical properties such as cation exchange capacity and aggregate stability (Geissen and Guzman, 2006). The combination of these soil stability variables with the infiltration-excess overland flow mobilises and transports the eroded particles in to the headwater channels, as simulated within Chappell et al. (1999a).

Mass movement relates to moisture status and shear strength of the regolith (Terzaghi and Peck, 1967; Sidle et al., 1985), together with the effects of tree root development (Sidle et al., 1985; Sidle, 1991; Dhakal and Sidle, 2003). Thus, a dynamic model of slope instability and hence the second source of sediments entering river channels should combine the effects of root-related slope strength with regolith moisture status.

As channels store sediments, with storage increasing with increasing scale (Curtis et al., 2005) an additional DBM transfer function is needed to parameterise the channel routing and storage of in-channel sediments, as simulated in Rowan et al. (2001).

3.8. DBM nutrient delivery model

When trees are planted, soil physicochemical properties change in response to the increased inputs of tree exudates and organic matter (Van Lear et al., 1995; Geissen and Guzman, 2006) and changes in levels of artificial chemicals, notably pesticides and inorganic fertilizer additions (FAO, 2004). Tree growth also affects chemical inputs to the soil system by changing the rates of weathering (e.g., Trudgill, 1988; Calvaruso et al., 2006). The changes to the soil combined with artificial chemical inputs, then change the soil water quality and nutrient status (Innes et al., 2004; Scott et al., 2004). The amount of soil–water then leaching into the rivers is the product of the concentration of the dissolved soil–water constituents (i.e., nutrients) and water entering the channels by return-flow. The resultant effect of in-channel nutrient transformations and removal between the headwaters and downstream reaches by vegetation and riverine processes then needs to be taken into account with a further DBM transfer function, as within the DBM river tracer studies of Young (1992).

Lastly, component water quality changes of sediment loss and nutrient loss can be combined into a single flux (e.g., kg km^{-2} h^{-1}) to allow the magnitude of water quality change to be compared with the magnitude of water quantity change.

4. Linking DBM models

4.1. Why link DBM models?

We need to use DBM models of time-series data collected at different scales to see which hydrological phenomena are observable at each scale, but these DBM models need to be combined to produce an integrated model of multiple hydrological phenomena at different scales. Chappell et al. (2006) has presented such an approach to linking DBM-defined model components into a single simulation model for tropical forestry management.

4.2. Modelling environment

A model structure combining inputs (i.e., rainfall, net radiation and dynamic tree characteristics) and the DBM-defined component models is presented in Figs. 2 and 3. This model structure, for simulating the potential water-flow, sediment and nutrient changes associated with reforestation, we call *for*SIM. For three reasons, *for*SIM is formulated within the Simulink (The MathWorks Inc., Natick, USA) simulation environment. First, Simulink runs within the Matlab (also The MathWorks Inc.) programming environment, which is used for the DBM modelling of each hydrological component. Second, the structure and parameters of a Simulink model are clearly visible to every user, allowing and indeed encouraging modification for application to particular sites. Thirdly, the modelling platform is already commercially available to any forest manager or hydrologist who wishes to use it to identify their reforestation-related research needs and priorities.

4.3. Rationale underpinning links between hydrological components

The starting point for the *for*SIM model is the proportion of the specified basin that has been reforested (Fig. 2, 'F1'). This specified value then provides input for the time-dependent functions of the: (i) mass of canopy leaves ('F2': Kittredge, 1948), (ii) mass of roots ('F3': Lugo, 1992), (iii) mass of biochemical exudates and litterfall ('F4': Keenan et al., 1995; Salako and Tian, 2005) and (iv) mass of artificial chemical inputs (FAO, 2004: Fig. 2, 'F5'). We consider that these functions characterise the main reforestation-related changes affecting the hydrological system. These 'forest drivers' (Fig. 3) have slow dynamics, with impacts evolving over decades (e.g., Sidle, 1991), in contrast to 'hydrological drivers' (Fig. 3) where the dominant drivers are very rapid, changing over hours. Thus, simulation of headwater micro-basins necessitates the model having at least an hourly time-step, and run for several decades. All fluxes (water, sediments and nutrients) are then represented as a mass per unit basin area on an hourly time-step.

Beneath the inputs, the *for*SIM model comprises of four interconnected 'vertical streams' (as in a waterworks control system: Figs. 2 and 3) of: (i) evapotranspiration ('eϕ', where ϕ is the number of the component DBM model, e.g., 'e2' in Fig. 2), (ii) riverflow generation ('wϕ'), (iii) sediment delivery ('sϕ') and (iv) nutrient delivery ('nϕ'). The upper portion of these streams describes those processes typically observable at

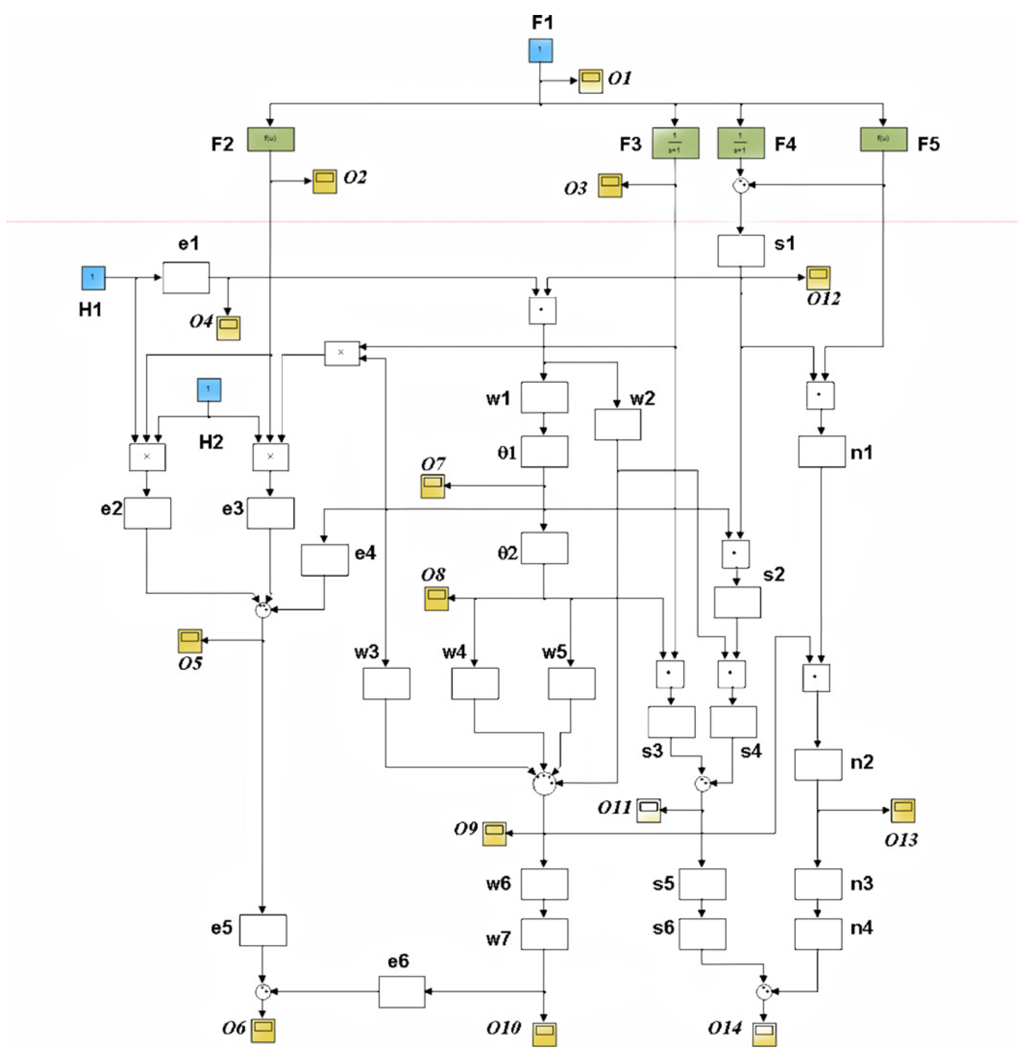

Fig. 2. The Simulink (The MathWorks Inc., Natick, USA) structure of the *for*SIM dynamic model for simulating the hydrological impacts of tropical reforestation, including the DBM-defined transfer function models.

Key

Forest driver/input:
F1 Watershed proportion forested
F2 Canopy mass
F3 Root mass
F4 Biochemical input
F5 Artificial chemical input

Hydrological driver/input:
H1 Precipitation
H2 Net radiation (or temperature)

Evaporation model:
e1 (1-e2) model
e2 Wet canopy evaporation model
e3 Transpiration model
e4 Soil evaporation model
e5 Regional evaporation model
e6 Open water evaporation (sea)

Waterflow model:
w1 Infiltration model
w2 Infiltration-excess overland flow model
w3 Lateral soil waterflow model
w4 Lateral regolith waterflow model
w5 Lateral rock waterflow model
w6 Headwater channel routing model
w7 Downstream channel routing model

Moisture status model:
$\theta 1$ Soil moisture status model
$\theta 2$ Regolith moisture status model

Soil and sediment models:
s1 Soil structure model
s2 Soil erodibility model
s3 Mass movement model
s4 Surficial erosion model
s5 Headwater delivery model
s6 Downstream delivery model

Nutrient and solute models:
n1 Soil nutrient status model
n2 Leaching model
n3 Headwater channel processing model
n4 Downstream channel processing model

Oscilloscopes (output):
O1 Proportion of area planted with forest
O2 Canopy mass time-series
O3 Root mass time-series
O4 Net precipitation time-series
O5 Local evapotranspiration time-series
O6 Regional evapotranspiration time-series
O7 Soil moisture time-series
O8 Regolith moisture time-series
O9 Returnflow / river generation time-series
O10 Water input to sea time-series
O11 Sediment load at source time-series
O12 Soil structural status time-series
O13 Dissolved load at source time-series
O14 Mass input to ocean time-series

Fig. 2. (*Continued*).

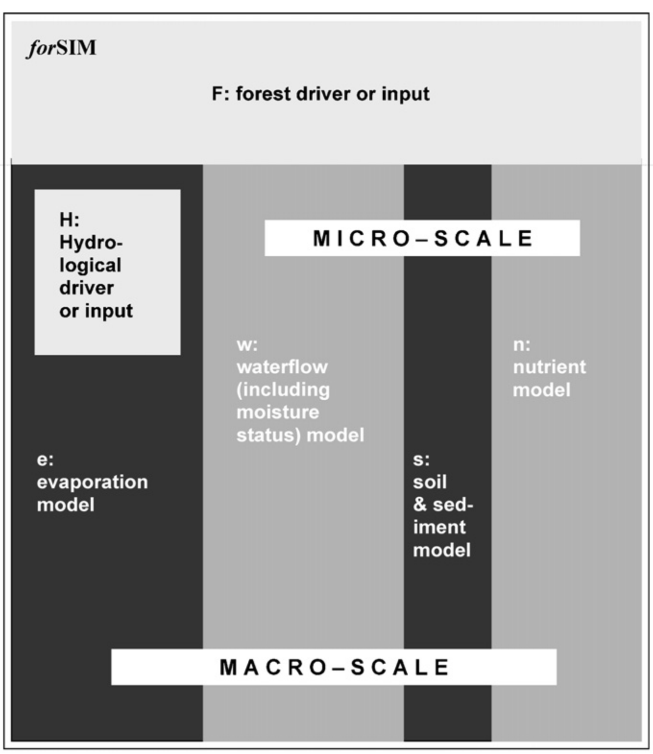

Fig. 3. The simplified elements of the *for*SIM dynamic model for simulating the hydrological impacts of tropical reforestation.

small-scales of plots, hillslopes and micro-basins (<50 km^2), while the lower portion shows the processes typically observable in riverflow records at macro-scales (i.e., 'e5', 'w7', 's6' and 'n4': >1000 km^2: Figs. 2 and 3). Thus, the *for*SIM model explicitly illustrates the topical issue of scale effects on hydrological processes (Blöschl and Sivapalan, 1995; Sidle, 2006), if only simply.

The linkages between the four streams are critical. Using the same input variable (e.g., soil moisture time-series) in several component DBM models reduces the number of inputs and internal states needed to simulate processes such as evapotranspiration and river generation. As a result, parametric uncertainty is reduced in the simulation scenarios. For example, the root mass time-series (i.e., 'O3': Lugo, 1992) is used to regulate: (i) the rate of root abstraction to supply transpiration ('e3') and (ii) shear strength against slope instability ('s3': Fig. 2). Similarly, the time-series of the soil structural index ('O12') regulates: (i) the rate of infiltration ('w1': Bonell, 2004; Grip et al., 2004) and infiltration-excess overland flow ('w2'), (ii) soil erodibility ('s2') and (iii) soil nutrient status ('n1'). Further, the net precipitation time-series ('O4') provides input to the infiltration-excess overland flow model ('w2': Fig. 1) and infiltration model ('w1'), which itself provides input (via percolation) to the models of lateral flow within the soil ('w3'), regolith ('w4') and rock ('w5'). All of these flows (i.e., 'w1 to w5') are combined to give the riverflow time-series ('O9':

Fig. 2). These water-flows provide direct input to the models of mass movement ('s3'), soil erosion ('s4') and leaching ('n2': Fig. 2).

5. Time-series observations from tropical studies pertinent to reforestation

5.1. Why time-series data are important in parameter identification

Defining an outline of the model structure is the first step in modelling (Beck et al., 1993) followed by identifying the best estimates of parameter values (e.g., a recession term in a transfer function, or mean permeability in a physics-based drainage basin model). Parameter identification within DBM modelling explicitly requires the availability of observed input and output time-series data. With physics-based modelling, it is often (incorrectly) stated that only field measurements of each parameter (e.g., permeability) are required (Bathurst, 1986). In practice, however, large-scale estimates of these parameter values have to be derived indirectly by inversion of numerical models of observed input and output time-series data (Beven, 2001c), and are only very loosely conditioned on the direct field measurements (Chappell and Ternan, 1992). This *de facto* approach to physics-based modelling has resulted from a combination of three factors. First, there are often an inadequate number of point measurements of each parameter (e.g., permeability) to make a statistically valid mean for model parameterisation, particularly within tropical regions. Secondly, the scale-dependence of parameters such as permeability, mean that point measurements cannot be used directly to condition model-parameter values at even micro-basin or hillslope scales (Chappell et al., 1998; Brooks et al., 2004). Thirdly, uncertainties due to instrument/technique errors in parameters such as permeability can be very large (Sherlock et al., 2000; Chappell and Lancaster, in press) making even statistically valid methods of 'upscaling' point measurements (e.g., Wen and Gómez-Hernández, 1996) invalid. With physics-based models, direct time-series observations of the output (e.g., streamflow) or internal-state (e.g., soil moisture content) are not required for model simulations to be undertaken. This sometimes means that the internal-state time-series are not validated, which means that the scientific rigor of these studies can be questioned (Klemeš, 2000). DBM modelling studies in contrast, must have time-series observations before a model is developed. As tropical hydrologists and foresters are increasingly aware of the lack of time-series of particular tropical forestry impacts (Thang and Chappell, 2004), a model which highlights those time-series needed to address the overall impact of reforestation on hydrology could be the stimulus for new measurement programmes. This is one of our key objectives in the development and later parameterisation and testing of the *for*SIM model.

5.2. Time-dependent reforestation and hydrological drivers

Numerous tropical plantation studies are available to quantify the relationship between time and canopy mass ('F2'; related to LAI) or root mass ('F3') in the early years of plantation development (e.g., Alder, 1978; Clark and Clark, 1999). There are, however, very few studies quantifying these relationships with tropical stands 30–100 years in age. The quantities of tree-related biochemical inputs to the ground from throughfall and litterfall ('F4'), has been quantified for some tree species used within tropical plantations (Keenan et al., 1995; Salako and Tian, 2005). Within micro-basin studies in the tropics, the inputs of artificial chemicals ('F5'), notably pesticides and fertilizers, has been quantified for plantations (e.g., Silver et al., 2005) and for agricultural land (FAO, 2004) that plantations sometimes replace.

Hourly rainfall data ('H1': Fig. 2) are commonly collected in tropical micro-basins ($<50\ km^2$) to record flashy tropical hydrological events. The energy inputs ('H2') conditioning wet-canopy evaporation and transpiration are expressed in the diurnal cycles of net radiation and temperature (Schulz and Jarvis, 2004). Historically, fewer research micro-basins in the tropics had hourly sampling of net radiation and/or air temperature, but increasingly, these data are being collected above tropical forests (e.g., Szarzynski and Anhuf, 2001; Malhi et al., 2002; Kumagai et al., 2004; Kume et al., 2006).

5.3. Runoff pathway, evapotranspiration and riverflow changes with reforestation

The water pathways that can contribute to streamflow are: (i) surface flow, including lateral flow in upper organic layers ('w2': Bonell and Gilmour, 1978), (ii) lateral flow within the soil (i.e., A and B soil horizons: 'w3'), (iii) lateral flow within a permeable regolith ('w4'), such as weathered granite and (iv) lateral flow with permeable rock ('w5': Bonell, 2004). Time-series of surface flow representative of micro-basins or larger can only be estimated using data from small plots, perhaps $0.0005\ km^2$ or less. The presence of water pathways within regolith ('w3'), perhaps at a depth 10 m below the ground surface is often overlooked (Bonell, 2004), however, evidence of this pathway is seen with damped stream hydrographs and associated DBM model parameters in tropical forest drainage basins (Chappell et al., 2005, 2007). The presence and effect of deeper pathways with permeable rock strata ('w4') is also similarly overlooked by many studies. Examinations of recent hydro-geological maps covering tropical South East Asia (Institute of Geography, 1999; Struckmeier and Richts, 2004) do, however, show the presence of such strata. Within temperate conditions, some time-series models quantify their impact on model parameters (Post and Jakeman, 1996; Sefton and Howarth, 1998). The key question to ask is whether reforestation does or does not affect deeper flows through permeable regolith or rock (including fissured rock)? If a significant proportion of the streamflow is generated by these pathways tens of metres below the ground surface, then percolation that moves rapidly to these depths, is soon at a depth that tree roots cannot extract the water (Pereira, 1959; Schenk and Jackson, 2002). Consequently, it is possible that the greater evapotranspiration typically seen in the early stages of growth of tropical plantations (Bruijnzeel, 1990; Scott et al., 2004), may not be so marked in these areas (Chappell and Bonell, 2005). Because of a lack of water budget studies in drainage basins overlying permeable rocks, we only have very limited evidence of this effect (Kirby et al., 1991, Table 35) and this should be a priority for new experimental studies. As we increase the size of drainage basin under study, river contributions from deeper in the system tend to increase. Thus, the effect of having deeper pathways on the nature of the impact of reforestation is likely to increase as we examine >1000 km^2 macro-basins. A further issue in quantifying the impact of reforestation on lateral flow in soil ('w2'), regolith ('w3') and rock ('w4') is our inability to measure the flows directly. The increasing use of environmental and artificial tracers (Bonell et al., 1984, 1998; Elsenbeer and Lack, 1996; Chappell and Sherlock, 2005; Genereux and Jordan, 2006) within tropical natural forests is one promising way to obtain such time-series data.

A wealth of rainfall (P_g or 'H1') and streamflow (Q or 'O9') observations have been used to quantify the effect of recent reforestation on annual evapotranspiration (i.e., P_g-Q) in tropical regions (Bruijnzeel, 1990; Scott et al., 2004). The main limitation of these studies is their short duration (<10 years). Some trees established in plantations have very high evapotranspiration rates in the first few years of rapid growth, but as the trees mature at ages perhaps in excess of 50 years, evapotranspiration rates are no higher than those of natural forests under the same hydro-climatic conditions (Vertessy et al., 2003). Many more time-series observations of long-established tropical plantations (Sharda and Ojasvi, 2006) need to be analysed or newly collected.

Tropical reforestation might change the flashiness (or strictly, recession constant of rivers: also 'O9'), and the DBM approach has already been used to attempt to identify these changes following natural rainforest harvesting and associated road construction at a micro-basin scale (Chappell et al., 2004a,b; Sidle et al., 2006). Others (e.g., Cuo et al., 2006) have shown how agricultural roads increase stream flashiness. The largest impact of trees on the direction of runoff pathways is likely to occur close to the ground surface (i.e., surface and soil horizons: Godsey and Elsenbeer, 2002). Thus, the largest potential for change of runoff pathways following reforestation will, therefore, occur when the dominant flow pathways are those of the surface ('w2') or laterally in the soil ('w3'). Studies that quantify the effect of reforestation on tropical water pathways and river time-constants are needed, comparable to those in temperate regions (see Jones and Grant, 1996; Robinson et al., 2003).

5.4. Sediment and nutrient flux changes with reforestation

Time-series data related to the two sources of suspended-sediments within headwater-rivers, namely component processes of erosion ('s3') and mass movement ('s4': Fig. 2), have been collected in the tropics (Douglas et al., 1999; Sidle et al., 2006; Walsh et al., 2006), however, the hourly time-series data relate to natural forests not plantations. While we know of the effects root development and organic matter incorporation on slope instability (Sidle et al., 1985, 2006; Collison and Anderson, 1996; Burton and Bathurst, 1998), those studies that relate these factors to the temporal delivery of sediments do so for temperate plantations or tropical natural forests, rather than tropical plantations.

For some large rivers (i.e., macro-basins) with daily and occasionally hourly suspended-sediment records, it is possible to quantify the effects of increasing in-channel storage of sediments at large scales ('s5 to s6': Fig. 2) using the methods described in the DBM study of Rowan et al. (2001). However, it is unclear how best to quantify the short-term rainfall characteristics ('H1') driving the sediment system for DBM models at these larger scales (Vongtanaboon and Chappell, 2004).

For particular experimental micro-basins, long-term and sometimes high-resolution datasets of nutrients are available through forest removal and reforestation cycles ('O13': Fig. 2). Examples include the Coweeta (Swank, 1988) and Plynlimon experimental drainage basins (Kirchner et al., 2000) in temperate USA and UK, respectively. Further, these data have been modelled with time-series methods (Kirchner et al., 2000). Within tropical regions, there are fewer nutrient time-series, but they do exist in micro-basins in Malaysia (Malmer, 1996; Grip et al., 2004), though they have yet to be modelled dynamically. These studies have shown that the enhanced nutrient leaching following cutting of tropical natural forest reduces dramatically over a few months (Malmer, 1996; Chappell et al., 2004b; Grip et al., 2004); but the long-term effect of the plantations established have yet to be reported. While soil and soil–water nutrient measurements within tropical plantations have been undertaken (Grip et al., 2004; Scott et al., 2004), the temporal resolution and duration, and link to the river nutrients is poor.

5.5. Summary of time-series data availability issues and implications

Many time-series data from micro-basins show that river-flow decreases in the first few years following plantation establishment in the tropics. Further, there is increasing availability of tower-based, micrometeorology, which can be used to simulate the evapotranspiration changes ('O5') that cause the riverflow decreases ('O9': Fig. 2). This loss of potential water yield from rivers is normally considered a negative impact (Calder, 2006). As very few studies have continued to monitor the water balance of plantations over several decades, we do not know how this negative impact is ameliorated as plantations move into senescent growth phases (Vertessy et al., 2003). We do not know whether this negative reforestation impact is still significant at the macro-scale ('e5': Chappell and Bonell, 2005) largely because of the lack of evaporation measurements integrated over the macro-basin scale.

We have some evidence of the positive impact of reforestation on soil erodibility, slope stability and nutrient status at the plot-scale (e.g., Roman et al., 2003; Jiang et al., 2006; Billings and Richter, 2006). The lack of sufficient time-series data of nutrient flux at micro-basin scales in the tropics

('O13') means that we cannot realistically generalise this potentially positive impact. The data situation is even worse for high quality sediment data ('O11'). Further, the dearth of time-series data of the tropical water pathways of infiltration-excess overland flow ('w2': Fig. 1), lateral flow within the soil ('w3'), lateral flow within the regolith ('w4') and lateral flow within the rock ('w5') means that it is difficult to simulate changes in the multiple sources of water ('O9'), sediments ('O11') and nutrients ('O13': Fig. 2).

While we might have the modelling techniques, some already applied in the tropics, it is the lack of time-series data for nutrients ('O13') and sediments ('O11') in particular, that currently prevent us from quantifying the negative and positive impacts of topical reforestation.

6. Conclusions

The potential DBM model structures, links and required time-series quantifying tropical reforestation impacts on hydrology presented within this paper are a first step in the modelling process. The *for*SIM model is a 'blueprint' to focus ongoing and future research on: (a) new time-series observations needed at micro-, meso- and macro-basin scales, and (b) the ways of simplifying the description of complex hydrological processes within a modelling framework. Following evaluation of the *for*SIM model with reforestation scenarios, we aim to further develop the model to simulate the hydrological effects of: (a) forest cutting (notably clearfell and selection-felling practices) of natural and plantation forests (Bruijnzeel, 2001; Chappell et al., 2004b) and (b) natural regeneration and enrichment planting within disturbed rainforests (Magnusson et al., 1999). We will also make versions of the model available, so that others can apply the approach to simulate other land-use changes such as the effects of conversion from high to low tillage agricultural practices (Moehansyah et al., 2004).

Any landscape manipulation always gives both positive and negative changes (Chappell, 2005). Sustainable forestry management solutions, therefore, require us to quantify all of the hydrological changes that *dominate* within the region under study, while presenting the results in a transparent and simplistic way, and maintaining consistency with the latest hydrological science. As a result, there are four observational datasets for reforested basins that must be sought to better parameterise the *for*SIM model:

(1) Time-series of catchment water balance data for plantations that extends over several decades are required to assess reductions in evapotranspiration with plantation age.
(2) Water budget observations for tropical macro-basins experiencing extensive and staged reforestation are required for a realistic assessment of water yield effects on a whole region,
(3) Nutrient and sediment losses from tropical micro- to macro-basins are needed to quantify the degree of change with plantation development and maturation and to compare with the water yield changes.
(4) Research on new methods of collecting data on component water pathways dominating at the micro-basin scale (e.g., lateral flow within the soil) are needed to simulate changes to the internal state dynamics controlling the river hydrograph, river sedigraph and nutrient losses.

By developing the *for*SIM model, we do not present a single answer, but a tool for underpinning further research particularly involving new field observations or reanalysis of existing field data.

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