basins. Local leadership, sometimes assisted by staff from government agencies or academic or civil society institutions, often features prominently in these cases.

The type of progress we have seen in some sub-basins also demonstrates local progress toward development of a “negotiation mindset” that will be required to effectively develop and implement solutions to many, if not most problems. There are usually costs and benefits associated with all potential solutions to a problem, and their distribution is frequently not even or balanced across the range of stakeholders involved. Thus, in order to achieve sufficient participation, this distribution of costs and benefits needs to be negotiated among concerned stakeholders. A negotiation mindset shifts emphasis from a focus on ‘winning’ or ‘losing’ to seeking an outcome wherein concerned stakeholders (at all levels) incur various costs and benefits that are mutually perceived as equitably distributed, as they jointly seek a ‘best possible’ outcome.

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For more information on the European water framework directive, please visit: http://www.europa.eu.int/comm/environment/water/water-framework/index_en.html

MODELLING TROPICAL FOREST WATERSHEDS: SETTING REALISTIC GOALS

By Nick A Chappell

Some rainforest watersheds in the tropics are natural buffers for water resources and ecology; others provide forest products, which sustain local livelihoods. The movement of waters containing chemicals and sediments needs to be known to underpin sound forest management practices; and watershed modelling is a key element in this learning process (Chappell *et al*., 2004b). We do, however, need to be realistic about what we can learn from these modelling results.

Forest hydrologists typically address one of four objectives when they model tropical rainforest watersheds. First, modelling can be used to test the consistency of existing theory and explore individual hydrological mechanisms in a systems context, addressing issues generic to the global hydrological community. These issues include how hydrological behaviour changes with watershed size, or how hydraulic characteristics can be measured over field-scales. Secondly, modelling can also show the relative importance of particular controls on hydrological behaviour within a particular setting; for example, the difference between watersheds with different rainfall regimes (e.g., cyclonic vs. non-cyclonic) or subsurface storage (e.g., aquifer vs. non-aquifer geology); these results can be used to help define simple conceptual models of watershed behaviour. Thirdly, models can be used to illustrate the impacts on hydrology of changes in land cover and/or rainfall regime.

Fourthly, modelling allows specific management questions to be addressed robustly; for example, how to define the width of stream buffer zones or roadside corridors. These four objectives have been addressed using a diverse (or bewildering?) range of watershed modelling approaches, each with their own advantages and limits.

Models can be 'static' being based on a long-term average behaviour; for example, the Revised Universal Soil Loss Equation (RUSLE) or NCYCLE model predict annual fluxes of sediment and nitrogen. Alternatively they can trace a daily (or shorter time-step) 'dynamic' being based on time-series measurements of frequently sampled variables such as rainfall, streamflow, transpiration or groundwater level. One might further classify dynamic watershed models in to: (i) physics-based, distributed models, (ii) conceptual, semi-distributed models, (iii) black box models, and (iv) data-based mechanistic (DBM) models.

Physics-based, distributed models are based on solving well-established hydrological 'laws' (e.g, Darcy, Chezy, Penman) while maintaining mass balance of water (and energy), and have model structures which allow measurements of distributed terrain characteristics to be utilised. Examples of these models include the Système Hydrologique Européen (SHE) model and IHDM. Given a local knowledge of the how terrain characteristics change with forest management (compaction, soil mobilization, etc) it is easy to see how such information can be incorporated within such models to simulate hydrological change. While computing power and the desire to make predictions of land-use change impact have increased over the past 20 years, we have become increasing aware that the terrain characteristics needed for our models are different to those we can measure. For example, any physics-based watershed simulation of rainfall-runoff response, nutrient export or erosion, demands measurements of ground permeability representative of lumps of the watershed perhaps 100x100 m in surface area. Our measurements on soil and weathered rock, in contrast, only include one hundredth of this, and are not readily related to the larger scale because of non-linearities in the hydrological system. Where fracture zones, natural soil pipes and gully systems are present this problem is magnified further (Chappell *et al*., 1998, 2004a). One might argue that the main success of these models is that they show the severe limitations of the data-sets of terrain characteristics available for watershed simulation.

Conceptual, semi-distributed models have much simpler model structures in comparison to physics-based models. This means that they simulate hydrological dynamics much more quickly than physics-based models and require less field data as input. These models have simple structures because they make prior assumptions about the dominant mechanisms operating and the nature of patterns of terrain characteristics. These models tend to be semi-distributed, in that the spatial distribution some terrain characteristics is incorporated (e.g., topography), while other characteristics are lumped in one or two dimensions (e.g., a single permeability profile or a two-layer subsurface model). Widely used examples of such models are TOPMODEL, BROOK, MAGIC, WEPP and HEC-HMS. The relative simplicity of such models has allowed them to be used to show the sensitivity of streamflow (or erosion or hydrochemistry) predictions to particular controls (e.g., topographic shape) and data limitations. A key constraint on belief in the results of these models surrounds how well the model parameters (e.g., model transmissivity) and model structures (e.g., whether there is one dominant fast and slow runoff pathway) relate to the true field data. Rather than simply assuming, for example, that one dominant fast and slow runoff pathway is present, perhaps we should see if the relationship between monitored rainfall and streamflow data has two identifiable components?

Black box models are invariability statistical models which are used to obtain the most efficient hydrological predictions (outputs) from one or more inputs, notably rainfall or upstream flows. The primary aim of many of these models has been to forecast river behaviour during storm events to predict over-bank flows (floods). A good example of such models is the Unit Hydrograph model. Fully black box models do not consider the hydrological mechanisms forming the rainfall-riverflow relationship. This means that while they give some of the best (least uncertain) short-term predictions of hydrological behaviour, there is no basis to alter the internal workings of the model to represent land-use or management effects.

Data-based mechanistic (DBM) models contrast with conceptual models (and indeed with physics-based models) in that in that they do not make prior assumptions about the hydrological mechanisms or pathways (e.g., the presence of one fast and one slow runoff pathway) operating in a particular watershed. Instead, the DBM technique involves fitting a wide range of mathematical relationships (notably transfer functions) to watershed rainfall, streamflow, and other data. Some of these relationships or models are statistically valid; these are then assessed for their consistency with the hydrological mechanisms observed to operate within the simulated watershed. This approach, therefore, seeks to obtain a model which is statistically sound, is consistent with the local hydrology and has the least number of model parameters (Chappell *et al*., 1999, 2004b). The latter objective constrains the uncertainty in the predictions of, for example, streamflow, stream sediment delivery or stream chemistry in comparison to physics-based and (most) conceptual models. Secondly, the DBM modelling technique, produces possible water pathways and watershed characteristics (e.g., residence times) that allow tropical hydrologists to think about new ideas, rather than constrain themselves to the role of certain pathways (e.g., overland flow) or characteristics observed at other sites in the tropics or even in temperate climates. It, therefore, helps focus new monitoring needs, an important issue given the cost of hydrometric and water quality equipment demanded by today’s scientists. Lastly, and perhaps most importantly, DBM more than any other technique, reinforces the importance of having good streamflow, rainfall, stream chemistry, etc. data on which to draw inferences after simulation. Within the tropics there are few data-series from case study sites (e.g., Babinda, Bukit Berembun, Bukit Tarek, Danum, La Cuenca, M’bé, Owena, Reserva Ducke) that allow us to generalise the natural behaviour of rainforest watersheds or quantify the impact of specific land management operations (Chappell *et al*., 2004b). In contrast, many other modelling approaches make very unrealistic predictions if compared with the limited number research observations that are available; sometimes giving the false impression that we fully understand the controls on tropical hydrological mechanisms (Chappell and Sherlock, 2005) and how they change with land disturbance. While DBM model use rarely falls into this trap, DBM models do have their own limitations. Critically, to study differences between locations or management practices, case study data must be available to undertake DBM simulations. Thus where there are no case studies available covering a particular combination of location and management attributes, it is difficult and perhaps unrealistic to construct a DBM modelling scenario.

While the latest modelling technologies need to be more extensively applied to all global regions, perhaps a larger issue limiting application of hydrological science to forest management problems is the lack of case study data for tropical forests. In tropical forest regions we still lack watershed-scale data on, for example, the hydrological value of sustainable forestry, a classification of rainfall-runoff response across tropical regions, robust simulation of nutrient dynamics, and many more issues. Without these case study data from protected and managed tropical forests, quantifying those environmental impacts that threaten people's livelihoods or local environment lacks credibility. Some modelling approaches CAN be used to identify and justify data needed by scientists from academic institutions across the tropics (and the wider global hydrological community). This is a realistic goal, while complex distributed simulations in data sparse environments that purport to show clear results and solutions may not be.

Five of our papers illustrating these issues are listed below. The UNESCO review text of Bonell and Bruijnzeel (2004) *Forests, Water and People in the Humid Tropics* (Cambridge University Press) contains further discussion of modelling tropical forest watersheds.

Chappell, N.A., Franks, S.W., and Larenus, J. 1998. Multi-scale permeability estimation in a tropical catchment. Hydrological Processes, 12, 1507-1523.

Chappell, N.A., McKenna, P., Bidin, K., Douglas, I., and Walsh, R.P.D. 1999. Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. Phil. Trans. Roy. Soc. Lond. B,, 354, 1831-1846.

Chappell, N.A., Bidin, K., Sherlock, M.D., and Lancaster, J.W. 2004a. Parsimonious spatial representation of tropical soils within dynamic, rainfall-runoff models. In Forests, Water and People in the Humid Tropics, Bonell M. and Bruijnzeel, L.A. (Eds), Cambridge University Press, Cambridge. p 756-769.

Chappell, Tych, W., Yusop, Z. N.A. Rahim, and Kasran, B. 2004b. Spatially-significant effects of selective tropical forestry on water, nutrient and sediment flows: a modelling-supported review. In Forests, Water and People in the Humid Tropics, Bonell M. and Bruijnzeel, L.A. (Eds), Cambridge University Press, Cambridge. p 513-532.

Chappell, N.A., and Sherlock, M.D. 2005. Contrasting flow pathways within tropical forest slopes of Ultisol soil. Earth Surface Processes and Landforms, 30, 735-753.

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