Hydrology in the Humid Tropic Environment (Proceedings of a symposium held at Kingston, Jamaica, November 1996). IAHS Publ. no. 253, 1998.

Identifying and modelling the hydrological patterns within a headwater humid tropical catchment

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Abstract Increasing pressure on the tropical environment requires a more thorough understanding of hydrological processes as part of reconciling the conflicting demands of economic development vis-à-vis sustainable land management. TOPMODEL is a physically-based semi-distributed topo-hydrological model. We test its validity in modelling streamflow dynamics (hydrograph) in a 1 ha tropical rainforest catchment in French Guyana. Another objective is to ascertain possible runoff generation mechanisms.

Identificacion y modelizacion de disenos hidrologicos en una cuenca de primer orden en la selva humeda tropical

Resumen Los incrementos de presion en un medio ambiente tropical requieren mucho mas que una compresion minuciosa de los procesos hidrologicos al encontrarsen dentro del marco de reconciliacion en el conflicto de las demandas entre un desarrollo economico contra una correcta y perrmanente administracion de las tierras. Utilizando TOPMODEL, un modelo basado fisicamente en una semidistribucion topo-hidrologica, comprobamos su validez en la modelizacion de la dinamica de los flujos de las corrientes (hydrograph) en 1 ha de selva lluviosa tropical en la Guyana Francesa. Otro de los objetivos ha sido una minuciosa validacion en el terreno de TOPMODEL con la posible constatacion de la generacion de mecanismos de desague.

INTRODUCTION

There is a dearth of more thorough understanding and representation of humid tropics hydrological phenomena (Bonell & Balek, 1993). The solutions of actual complex environmental problems can be dealt with only in the context of physically-based distributive models (Beven, 1992). Our research work presented in this paper combines these modelling efforts. In using a topographically-based, hydrological model, TOPMODEL (Beven & Kirkby, 1979) at the scale of a small headwater forested catchment we investigate whether it is a sufficiently reliable conceptual tool for representing stormflow generation processes. This study represents, with the possible exception of the studies performed in Côte d'Ivoire (Quinn *et al.*, 1991) and in northeast Queensland (Bonell *et al.*, 1996), the first successful application in the humid tropics of a more physically-based model.

The research programme was undertaken within the framework of a more general study of geochemical processes in the moist tropical forest: Programme d'Etude de la Géosphère Intertropicale (PEGI).

THE PHYSICAL BACKGROUND

The study was conducted in French Guyana. The catchment investigated, known as catchment B, belongs to the long-term experimental catchment studies associated with the Ecologie, Erosion, Experimentation (ECEREX) operation (Fritsch, 1990; Sarrailh, 1990). It is situated 40 km from the coastline near the town of Sinnamary. The catchment area is 1.5 ha. The annual water balance consists of 3300 mm precipitation, of which 1200 mm has been estimated for evapotranspiration and 600 mm for runoff (Fritsch, 1990). The water balance deficit is determined by the small scale of this catchment. This cannot take into account percolation towards the deep groundwater body, which participates in the regional groundwater circulation. Thus there is no permanent water table in superficial soil horizons in the catchment which would contribute to the organized drainage network and stormflow at this scale.

The soils are complex, composed of several layers of contrasting hydraulic conductivity about 25 m above the original rock (Guehl, 1984). This system enables locally quick saturation of the more shallow, permeable horizons.

The vertical and lateral organization of the horizons in the studied catchment is determined by the strong pedological transformations which divide the catchment into two zones of contrasting hydrodynamic environments: a deep drainage zone situated upslope and a superficial lateral drainage zone situated midslope and downslope in more weathered soil (Grimaldi & Boulet, 1989). The extremely high lateral heterogeneity is difficult to take into account within hydrological modelling.

EXPERIMENTAL DESIGN AND DATA

We monitored experimental catchment B during four intensive campaigns within the rainy seasons; two of them in January and May 1992 and the others in May 1993 and May 1995. The timing of these campaigns was intended to coincide with the period when near-instantaneous, perched water table frequently occurred during storms in response to the "near-saturated" catchment conditions. The instrumentation comprised a raingauge network (31 gauges distributed at random along a 100 m section) supported by a hydrometric network of a hillslope transect consisting of tensiometers. In addition, there was a stream discharge station at the outlet which comprised a water level recorder and a water level scale chart adjoining a thin plate V-notch weir.

During four field campaigns we could capture only two storms which were appropriate for the testing of TOPMODEL. The cause was insufficient rainfall to create the appropriate antecedent moisture conditions necessary to initiate streamflow discharge in a catchment with no permanent water table. The two storms which produced significant runoff took place on 24 May 1992 and 15 May 1993.

METHODS

TOPMODEL is a free assemblage package of ideas and concepts for hydrological modelling of the runoff generation processes. Full details are given in Beven *et al.* (1995). The modular structure has been kept simple enough to enable adjustments to the specific modelling needs of particular catchments to be accommodated. This helps the model to still evolve and enables better description of hydrological processes. The number of parameters is kept low and they are intended to be physically interpretable.

A preliminary study of the stream hydrograph and tensiometer records indicated possibilities for saturation overland flow and shallow subsurface stormflow (Chorley in Kirkby, 1978, pp. 371–373) during storms across almost the whole catchment in spite of the lateral soil heterogeneity (Fritsch, 1990). This hydrodynamic behaviour provided a good basis for the application of TOPMODEL.

The resulting topographic index map of 2.5 m grid was computed from a DTM derived from a 1 m contour map, using the multidirectional algorithm (Quinn *et al.*, 1995). The topographic index expresses according to the TOPMODEL concept the propensity of the pixel to be saturated. The resulting spatial pattern of the topographic index (Fig. 1) reproduces well the field observations of saturation area locations.

TOPMODEL was applied using 15 min time increments, which corresponded with the time scale of field monitoring and with our perception of the stormflow generation dynamics in the study catchment. We did not evaluate baseflow recession curves because there is no permanent flow in the catchment. Consequently we could not estimate the exponential subsurface recession parameter, *m*, the most sensitive

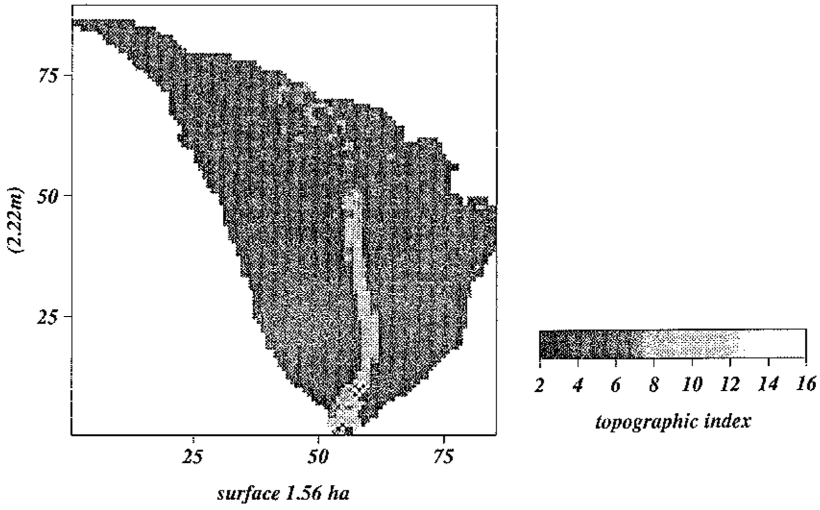

Fig. 1 Distribution of the topographic index.

parameter used in TOPMODEL theory (Beven *et al.*, 1995). The latter characterizes the soil storage–catchment discharge relationship of the catchment. Nevertheless the storm hydrograph recession curves corresponding to "quickflow" determined *m* as being 0.002–0.003 m. This value indicates that catchment saturation can occur within an infiltration equivalent depth of about 2–3 mm.

The other physically meaningful parameter is *SRMAX*. Assuming the "field capacity concept" *SRMAX* represents the field storage demand, i.e. the maximum amount of matrix water that can be held against gravity. The *SRMAX* value is conceptualized in current TOPMODEL theory as a root zone reservoir. It has to be exceeded in order to initiate soil water percolation and the water table recharge. In the particular case of our catchment the root zone conforms with the principal soil layer which constitutes the streamflow water transfer downslope. In this case the latter responds to not only the evapotranspiration demand of the tropical forest but also determines the rate of deep leakage loss. Using the ECEREX database we undertook a rainfall–discharge analysis which showed that the catchment responds only after having received about 10 mm of rainfall within the 12 h prior to the storm. We used this value in the model calibration of *SRMAX*.

The other difficult to estimate parameter, is linked to the actual evapotranspiration during the storms (Shuttleworth, 1989). The only estimates of potential evapotranspiration were provided at a monthly or decadal scale using classical relationships (Penman, 1948). The corresponding potential evapotranspiration rate is 3 mm day^{-1} (Fritsch, 1990). In fact we considered the allocated value as a lumped loss reservoir, which takes into account both evapotranspiration and deep leakage losses occurring in the catchment. It was set at 0.0008 m per 15 min to be sustained according to the current *SRMAX* moisture availability.

The initial discharge (Q_{init}) being nonexistent, this value in the model was initially set to a realistic initial value.

Unfortunately we do not have any estimates of hydraulic conductivity to calibrate the parameter SK_0, the saturated hydraulic conductivity in the point where the water table just intersects the surface. In fact, when we later considered the tensiometric information we discovered possibilities for important macropore and pipe networks capable of carrying substantial amounts of water. Such pipe and macropore networks are thought to be an important aspect of the rainfall–runoff relationship. These preferential pathways also violate the "field capacity concept" assumed in TOPMODEL. The significant impact of macroporosity can be represented by a high hydraulic conductivity value however its occurrence is also variable depending on the overall soil moisture status of the catchment. The manually optimized value was set at 0.55 m s^{-1}.

RESULTS

The two recorded storms were of a similar order of magnitude. However we would like to point out their principal differences. In May 1992 the runoff commenced only after about 12 mm of rain had occurred. At this point the upper soil profiles could be saturated to initiate discharge, and then streamflow developed in line with the magnitude of rainfall input. A total rainfall of 54 mm produced a runoff of about 16 mm. In contrast, in 1993, only 7 mm of rainfall was necessary for discharge initiation. However, almost the same total rainfall, 57 mm, produced much more runoff, about 28 mm. Rainfall intensities were not significantly different between the two storms and cannot explain the considerable difference in total runoff. One possible explanation is the fact that the period prior to the storm in 1993 was much wetter which thus enabled a better interconnection of localized saturation across the slope. This resulted in almost a doubling of runoff volume recorded in the May 1993 event compared with that of May 1992.

Figure 2 presents the best fit for the simulation of 24 May 1992. The simulated hydrograph exhibits an acceptable fit both in shape and timing. The manual optimization efficiency of the run achieved about 96% according to the Nash efficiency criterion. The most sensitive parameter was *m* reflecting the hydrograph recession pattern and then *SRMAX* characterizing the root zone storage capacity. The optimized value of *m* is 0.0035 m and of *SRMAX* 0.011 m.

Figure 3 shows the simulation of the 15 May 1993 hydrograph using the same set of parameters, except for the value of initial discharge (Q_{init}), which was adjusted, in

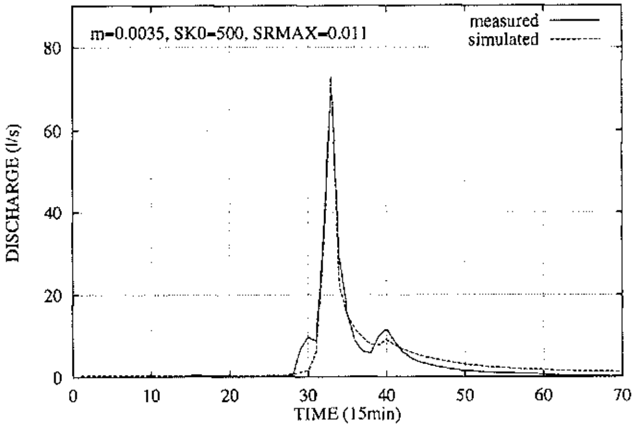

Fig. 2 Simulation of the stormflow hydrograph of 24 May 1992.

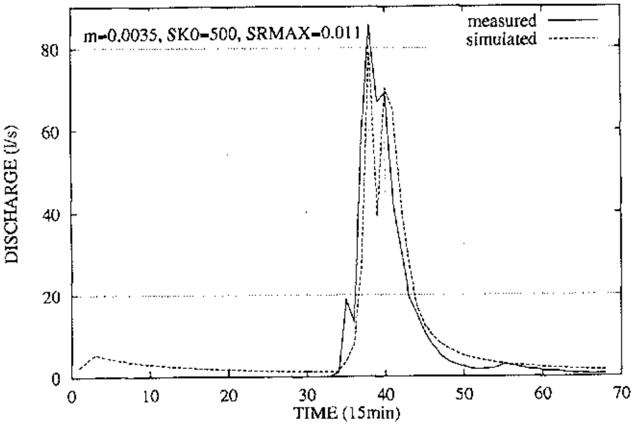

Fig. 3 Simulation of the stormflow hydrograph of 15 May 1993 after the rainfall corrections.

order to take into account the more saturated conditions of the catchment. This run was only 88% successful. We searched for a possible reason for the lower efficiency.

Subsequently, we found an inconsistency in the spatial resolution of the rainfall data. A spatial rainfall field structure was detected for the higher precipitation events, such as the one described for 15 May 1993, which had not previously been appreciated until further monitoring had been undertaken (Moličová & Hubert, 1994). Thus the computed average value could not be extrapolated to the catchment as a whole, based on the raingauge network distributed within 100 m section only (Delhomme, 1978).

The above is a very significant point to highlight in the context of modelling. First, the erroneous rainfall record showed an extreme TOPMODEL sensitivity to data input, which should be recognized by TOPMODEL users (Franchini *et al.*, 1996). Second, this example demonstrates the utility of quantitative hydrological modelling, that is, using a model as a tool of data control and system consistency.

Having resolved the problem relative to rainfall resolution, we suspected that there was another aspect responsible for the less successful simulation of the storm of 15 May 1993 compared to that of 24 May 1992. This could be the larger rate of macropore flow associated with the longer duration of rainfall. In addition, the higher antecedent moisture status of the catchment was more favourable to a higher rate of macropore flow.

As the outlet discharge represents an integration of effects within the catchment, it might be possible for an apparently satisfactory calibration to be produced on the basis of erroneous but compensating representations of internal processes. Consequently, for the distributed physically-based models, the consideration of observations of internal status of the catchment is also implied. Thus the maps of soil moisture status predicted by TOPMODEL were generated across the both events. The runoff generation pattern suggested by these maps reproduces well the streamflow generation dynamics across the time and space, and the location of saturation excess areas. The maximum expansion of the saturated area can be demonstrated in Fig. 4 which presents the maximum moisture status of the catchment at the time of peak for the storm of 15 May 1993.

DISCUSSION AND CONCLUSIONS

In spite of TOPMODEL's successful predictions, the tensiometer profiles and the soil characteristics analysis indicate the likelihood of substantial macropore flow occurring during the storms within subsurface layers. Such macropore flow violates the three TOPMODEL assumptions: exponential decline in transmissivity, the field capacity concept and Darcian flow.

Regardless of the above reservations it would appear that TOPMODEL provides satisfactory approximation of runoff predictions and spatial runoff generation dynamics. The possible reasons are the presumed low hydraulic conductivity of the subsoil coupled with the absence of an additional deep groundwater body. The latter contribution elsewhere in the humid tropics has caused difficulties in the application of topographical physically-based runoff models in tropical rainforest environments (Quinn *et al.*, 1991; Bonell *et al.*, 1996).

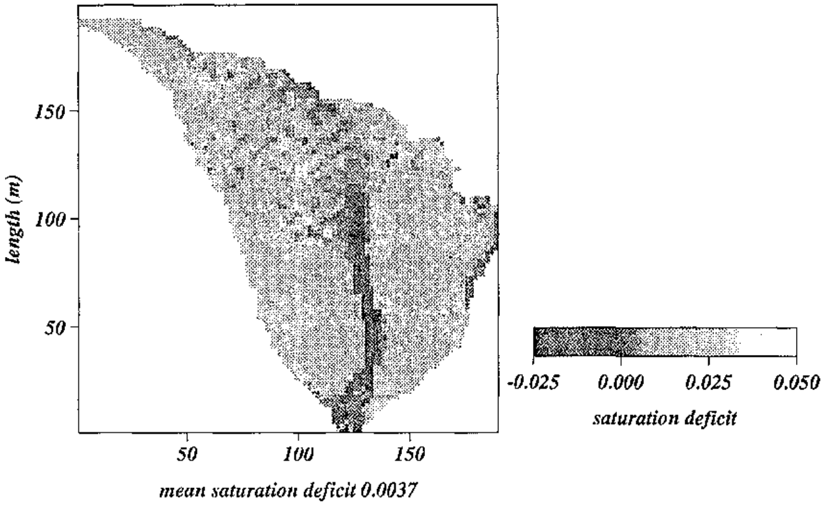

Fig. 4 Catchment moisture status at the peak of the 15 May 1993 stormflow event.

Acknowledgements We acknowledge CNRS-INSU (France) for financial support of the PEGI program. Then ORSTOM (France) for field facilities met in French Guyana and UNESCO (Division of Water Sciences) for travel assistance for the TOPMODEL Symposium held in Lancaster, UK, 20–24 September 1995.

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