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Model intercomparison to explore catchment functioning: Results from a remote montane tropical rainforest

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ABSTRACT

Catchment-scale runoff generation involves a complex interaction of physical and chemical processes operating over a wide distribution of spatial and temporal scales. Understanding runoff generation is challenged by this inherent complexity – the more uncertain step of predicting the hydrologic response of catchments is that much more challenging. Many different hypotheses have been implemented in hydrological models to capture runoff generation processes and provide hydrologic predictions. These concepts have been developed based on extended field observations. Here we propose inferring water flux understanding and catchment exploring through the application of a variety of available hydrological models as a mechanism to build upon and extend models that have been developed to capture particular hydrological processes. We view this ensemble modeling strategy as particularly appropriate in ungauged catchments. The study is carried out in a tropical montane rainforest catchment in Southern Ecuador. The catchment is 75 km^2 and is covered by forest in the south, while the northern slopes have been partly deforested for grazing. Annual rainfall is highly variable, reaching up to 5700 mm per year in the upper parts of the catchment. To explore the dominating runoff processes, an ensemble of 6 hydrological models with different structures applied over different levels of both spatial and temporal detail was developed. The ensemble includes spatially lumped (HBV-light), semi-distributed (HEC-HMS, CHIMP, SWAT, LASCAM) and a fully distributed model (HBV-N-D). The hydro-statistical toolkit WETSPRO was used to characterize simulated and observed hydrographs. Estimated baseflow indices, flow minima and maxima, flow duration curves and cumulative errors were generated and compared among the ensemble of models. This process facilitated the exploration of processes controlling runoff generation, enabled an evaluation of the applicability of the screened models to tropical montane rainforests, and provided the capacity to evaluate and explain where different models failed.

1. Introduction

Water is a key component of ecosystems that facilitates energy transfers, triggers erosion, drives patterns of biodiversity and acts as a key agent of lateral transport for particulate and dissolved nutrients. A variety of environmental models have been developed to evaluate ecosystem function, including issues related to climate, land-use change and water quality (Cook and Vizy, 2008; Krysanova et al., 1998; Riley and Stefan, 1988; Veldkamp and Lambin, 2001). These models are generally coupled with existing concepts defining the hydrological flow response. The combination of field and modeling studies has contributed to a more complete understanding of the hydro-ecological cycle, and is crucial in the investigation of how future land use and climate change will alter water and solute fluxes. These fluxes influence a wide variety of ecosystem services, including nutrient storage, erosion reduction, water supply, potential hydroelectric production and the management of ecological resources (Caballero et al., 2004; Vanacker et al., 2007; Célleri and Feyen, 2009).

Increasingly, attention is focused on tropical regions to better understand hydrological fluxes and processes, as well as interactions between biogeochemical and ecological processes (Bruijnzeel, 2004; Hilton et al., 2008; Guardiola Claramonte et al., 2010; Figueiredo et al., 2010). These types of studies approach fundamental issues faced by those living in tropical areas: as demand

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for water resources increases and as water availability changes in space and time, basic knowledge regarding hydrologic function is a crucial component of predictive tools that can contribute to informed decision-making around water resource planning.

Field studies in runoff generation processes in tropical regions have been mainly developed to understand the anthropogenic impact on water fluxes and erosion due to land use change for timber production (Bruijnzeel, 2004). Apart from the changes in the overall water budget, land use change also impacts the timing and magnitudes of peak flows, as well as dry weather runoff or seasonal patterns, indicating that runoff generation and storages are changed as well (Bonell, 1998). Following typical soil and landscape properties of tropical environments, Elsenbeer (2001) presented a general concept of runoff generating processes operating in these regions. A key element of this framework is the occurrence of rapid declining permeability which leads to the development of lateral subsurface flows. Depending on the bedrock topography this lateral flow in turn can produce upslope return flows and localized saturation, leading to the development of saturation excess overland flow.

Research in tropical montane forests and adjacent cleared pasture land in the Rio San Francisco valley, Ecuador, has substantially increased our understanding of ecosystem function, and in particular, has raised fundamental issues regarding the applicability of the conceptual strategy outlined by Elsenbeer (2001). In pristine areas of the catchment, due to soil physical characteristics and the high precipitation rates, quick flows dominate small catchment hydrographs (Goller et al., 2005; Wilcke et al., 2008; Bauer et al., unpublished results). While this behavior is entirely consistent with the conceptual model of Elsenbeer (2001) it is important to recognize that only 68% of the San Francisco catchment is pristine forests. Recent findings in higher order streams in the catchment challenge the concept from Elsenbeer (2001). Investigations of hydrochemistry (Bücker et al., 2010) and Mean Transit Time (MTT) (Crespo et al., unpublished results-a) in a nested catchment approach, including catchments with a large share of pasture, indicate that baseflow contribution dominates flow generation, despite steep slopes, shallow soils and intense rainfall rates of 5000 mm yr^{-1} and even more.

Our picture of generally declining permeability with depth might be too simplistic, given the widespread occurrence of landslides in this (and many other) tropical montane catchments, that lead to a very complex heterogeneity of soil types on the small-scale (Huwe et al., 2008). In fact, pasture sites in the catchment have been reported where saturated conductivity has increased with soil depth (Huwe et al., 2008; Crespo et al., personal communication). In contrast, Zimmermann and Elsenbeer (2008) reported almost the opposite findings for the same research area. They found a general decrease of soil permeability with depth, only marginal differences between landslide impacted and natural forests, and a severe reduction after forest conversion to pastures. It is therefore likely that runoff generation is defined by a suite of interrelated processes, including transmissivity feedback, piston flow, saturation excess overland flow as well as subsurface flow.

The processes outlined in Elsenbeer (2001) have been implemented into hydrological simulation tools and applied to tropical environments (Molicova et al., 1997; Campling et al., 2002; Kinner and Stallard, 2004). Vertessy and Elsenbeer (1999) further included the topographic location, along with the rapid depth dependent decline in permeability. Apart from these model applications, all of which are based upon the TOPMODEL approach (Beven and Kirkby, 1979), little work has been put into the testing of other hydrological model concepts in tropical montane ecosystems despite the plethora of models that have been developed for Northern America and Europe. A number of studies have, however, recently emerged. Notter et al. (2007) applied the NRM3 stream flow model to several mesoscale catchments in the Mt Kenya region to investigate the potential effects of climate change on water resources. The impact of climate change on water resources was also studied for a headwater in the Nile basin using the SWAT model (Kingston and Taylor, 2010). Despite the use of both manual and automatic model calibration techniques SWAT poorly performed for daily as well as monthly discharges. To investigate hydrology and associated non-point source pollution, the HSPF model was utilized in a Taiwanese catchment (Chang et al., 2008). The model clearly underestimated low flows and recessions of peak flows, a fact the authors attributed to a limitation of input data including geology, soil properties and groundwater condition. In a study using the HBV-light model, land use change impact through burning and harvesting of pine trees on water yield, and evapotranspiration were analyzed for a small lowland, though steep catchment on Fiji island (Waterloo et al., 2007). In this case, the model was successfully calibrated to provide good model efficiencies for simulations of pre- and post-harvesting periods. The research area was characterized by moderately to very steep slopes, high annual rainfall rates and well-drained soils on slopes and ridges, all typical for tropical montane ecosystems as well. Uhlenbrook et al. (2010) utilized the same model to analyze catchment behavior in the Upper Blue Nile river basin. Due to the poor input data quality and model deficiencies, they concluded that the HBV-light model was useful for general water resources planning but not for predicting dominant hydrological processes. To better represent vertical energy and water fluxes the land-surface scheme ISBA has been used to predict discharge in a high mountain valley of Bolivia. Here, the routing scheme was identified as a key model component for a good prediction of discharge, while the contribution of deeper soil horizons or groundwater to runoff was of minor importance (Caballero et al., 2004, 2007).

There are tremendous numbers of existing hydrological models, many of which can capture processes operating in tropical catchments. Despite this fact – or perhaps even because of it – the objective selection of a most appropriate model remains challenging. But perhaps rather than focusing on the application of a single, potentially incorrect model structure, the focus of modeling studies should instead be on the evaluation of a variety of different models, representing different mechanisms for defining runoff generation. Under this strategy, the process may lead towards a suite of plausible model structures and, as importantly, to the rejection of others. Model intercomparison has been suggested as one method to test the capacity of models to reflect catchment behavior (Refsgaard and Knudsen, 1996; Reed et al., 2004; Breuer et al., 2009). One of the primary goals behind this type of ensemble modeling is to provide a common backdrop against which a variety of different models can be evaluated, providing the means to evaluate and reject either different model components or whole models entirely. The process has been used to evaluate model structural uncertainty (Reed et al., 2004; Refsgaard et al., 2007; Breuer et al., 2009; Viney et al., 2009a), but also, as is the case in this work, as a comparative strategy to delineate a sub-set of models that are consistent with available observations. The modeling structures that make up the subset can then be further evaluated as potentially useful descriptions of the runoff generation mechanisms operating within the catchment. While purely observational strategies are the preferred methods to develop understanding of catchment processes, in ungauged catchments, where data is sparse or unavailable, we require alternative mechanisms.

We applied a set of different types of hydrological models, ranging in complexity from simple lumped to fully distributed approaches to test the models' applicability in simulating the rainfall-runoff reactions observed in the San Francisco catchment. We aimed at learning from model behavior to derive catchment understanding, a method recently also proposed by Uhlenbrook et al. (2010) for a tropical montane catchment in Ethiopia. We