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Towards a physically-based multi-scale ecohydrological simulator for semi-arid regions

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The use of numerical models as tools for describing and understanding complex ecohydrological systems has enabled to test hypothesis and propose fundamental, process-based explanations of the system system behaviour as a whole as well as its internal dynamics. Reaction-diffusion equations have been used to describe and generate organized pattern such as bands, spots, and labyrinths using simple feedback mechanisms and boundary conditions. Alternatively, pattern-matching cellular automaton models have been used to generate vegetation self-organization in arid and semi-arid regions also using simple description of surface hydrological processes. A key question is: How much physical realism is needed in order to adequately capture the pattern formation processes in semi-arid regions while reliably representing the water balance dynamics at the relevant time scales? In fact, redistribution of water by surface runoff at the hillslope scale occurs at temporal resolution of minutes while the vegetation development requires much lower temporal resolution and longer times spans. This generates a fundamental spatio-temporal multi-scale problem to be solved, for which high resolution rainfall and surface topography are required. Accordingly, the objective of this contribution is to provide proof-of-concept that governing processes can be described numerically at those multiple scales.

The requirements for a simulating ecohydrological processes and pattern formation with increased physical realism are, amongst others:
i. high resolution rainfall that adequately captures the triggers of growth as vegetation dynamics of arid regions respond as pulsed systems.
ii. complex, natural topography in order to accurately model drainage patterns, as surface water redistribution is highly sensitive to topographic features.
iii. microtopography and hydraulic roughness, as small scale variations do impact on large scale hillslope behaviour
iv. moisture dependent infiltration as temporal dynamics of infiltration affects water storage under vegetation and in bare soil

Despite the volume of research in this field, fundamental limitations still exist in the models regarding the aforementioned issues. Topography and hydrodynamics have been strongly simplified. Infiltration has been modelled as dependent on depth but independent of soil moisture. Temporal rainfall variability has only been addressed for seasonal rain. Spatial heterogenity of the topography as well as roughness and infiltration properties, has not been fully and explicitly represented. We hypothesize that physical processes must be robustly modelled and the drivers of complexity must be present with as much resolution as possible in order to provide the necessary realism to improve transient simulations, perhaps leading the way to virtual laboratories and, arguably, predictive tools.

This work provides a first approach into a model with explicit hydrological processes represented by physically-based hydrodynamic models, coupled with well-accepted vegetation models. The model aims to enable new possibilities relating to spatiotemporal variability, arbitrary topography and representation of spatial heterogeneity, including sub-daily (in fact, arbitrary) temporal variability of rain as the main forcing of the model, explicit representation of infiltration processes, and various feedback mechanisms between the hydrodynamics and the vegetation. Preliminary testing strongly suggests that the model is viable, has the potential of producing new information of internal dynamics of the system, and allows to successfully aggregate many of the sources of complexity. Initial benchmarking of the model also reveals strengths to be exploited, thus providing an interesting research outlook, as well as weaknesses to be addressed in the immediate future.