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ACCOUNTING FOR LANDSCAPE HETEROGENEITY IN HYDROLOGICAL MODELS: A REVIEW

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ABSTRACT– Accounting for landscape heterogeneity in hydrological models is not recent. Freeze and Harlan (1969) made an approach to address this issue, based on what was best known about physical process in partial differential equations used to describe water movement. That approach was adopted by several hydrological models, so called physically distributed models. Although applications have been constrained by computational power, nowadays there have been considerable efforts in using the Freeze and Harlam approach at large-scale problems, albeit at ever increasing complexity and computational demand and, mostly, scale problems in measured and estimated parameters, without necessarily improving predictions. A less demanding alternative to address landscape heterogeneity is by classifying landscape features by hydrological similarity, i.e. units that respond similarly to model inputs. Each unit having its own set of parameters and/or structure. The principle of landscape coevolution sheds light on the possibility of using observable landscape features, such as topography and vegetation, to address hydrological similarity. It can provide valuable insights in hydrological understanding, prediction in ungauged basins and in a changing environment.

Keywords – Landscape heterogeneity.

INTRODUCTION

Hydrological models with realistic physical representation, in terms of process and spatial complexity, are desirable in order to access the impacts of climate change, land use change and to allow climatic and hydrologic forecasts with more reliability. However, hydrological behaviour at large scale is still poorly understood, mainly because of the lack of observable parameters at relevant catchment scale and process complexity representation.

The search for physical realism is not recent. In the early stages of computational hydrologic modelling, most models described rainfall-runoff process in a lumped way. They were well-suited for most of the questions involving hydrology at the time. During the last few decades, however, different scientific questions began to emerge, such as ‘what is the impact of climate change and land

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use change in hydrological processes?' and 'what is the role of different land surface characteristics in the water cycle?'. Along with that, with the advance of computer power and measuring techniques by remote sensing, it became possible to account for spatial heterogeneity in hydrological modelling and to develop models in a distributed way. The attention, then, began to be addressed to physical realism and distributed representation of the hydrological processes.

There are two main branches in the consideration of landscape heterogeneity in hydrological models: the physically based distributed representation and the conceptual representation through hydrological similarity. This review tries to describe relevant aspects in both of the approaches, highlighting the strategies used to account for the heterogeneity of hydrological processes.

PHYSICALLY BASED DISTRIBUTED REPRESENTATION

The equations of physical processes controlling water fluxes at catchment scale were remarkably described by Freeze and Harlan, in 1969. The non-linear partial differential equations that are used to describe water movement are defined assuming a reliability between physical knowledge and data availability. This way, the domains of soil fluxes and overland fluxes are represented, respectively, by the Darcy's law and the Saint-Venant equations. Most physically-based models today are based on the Freeze and Harlan blueprint, many of them using simplifications of the equations proposed (Beven, 2012).

The SHE-model (Abbott et al., 1986) is a notable case that uses the Freeze and Harlan framework. It divides the catchment into rectangular grid elements, each one having its own model components for interception, evapotranspiration, snowmelt and unsaturated zone flow. The elements are linked by a two-dimensional surface runoff component solving the diffusion approximation of the Saint-Venant equations, a two-dimensional groundwater component solving the Boussinesq equation, a one-dimensional unsaturated zone component solving the Richards equation and a one-dimensional evapotranspiration component solving the Penman-Monteith equation. Surface and subsurface domains are coupled by internal boundary conditions.

With the increasingly growing computational power, recent years have seen physically-based models being applied with high resolution at large extents. An example is the work of Maxwell et al. (2015) that used the ParFlow model (Ashby and Falgout, 1996; Kollet and Maxwell, 2006) over nearly the whole continental United States. The ParFlow was firstly designed as a groundwater model, but later modifications by Kollet and Maxwell (2006) integrated a surface flow component. It solves both surface and subsurface domains simultaneously, with robust methods of numerical solutions. The surface domain is described by a two-dimensional kinematic wave equation, while subsurface is described by a three-dimensional Richards equation for variably saturated flow.

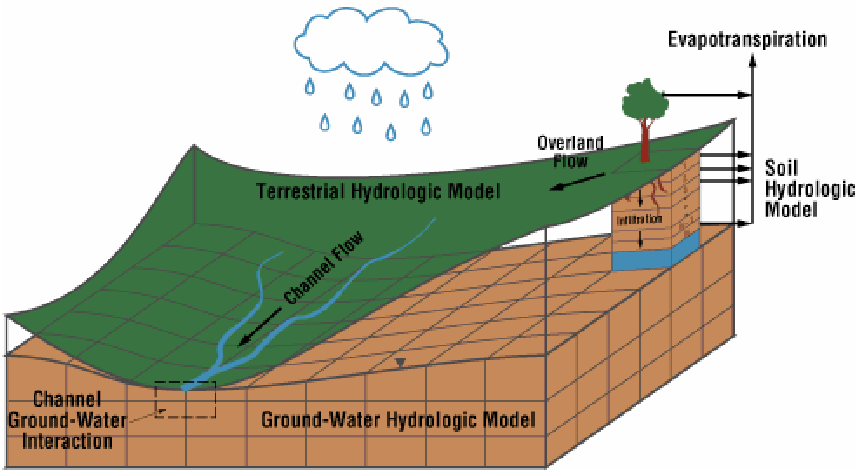

Figure 1 – Physically based representation of hydrological processes. Source: (Yu et al., 1999).

One problem with applications of physically-based models is that they require the specification of many parameter values. The finer the element scale, the more parameter values. Supposedly, all parameter values are field measurable, however, there is a scale issue in derivations of the measured values and the element size used in the model. Furthermore, many parameters are dependent on the state of other variables in the model, needing to be related by transfer functions, which require more parameters.

Another issue involves the computational resources necessary to perform the simulations. Even with the advance in numerical solution methods and computational power, it is still required a lot of machine processing to applications at large scale and only a few research centres have the wherewithal.

It is worth noting that physically based models do not necessarily improve predictions, as their use is constrained by relatively small and sufficiently gauged catchments (Gharari et al., 2015). A simpler way to maintain distributed description of catchment responses without the detailed process representation of the models above is using a conceptual approach, which uses a form of distribution function to represent the spatial variability of runoff generation. This will be described next.

CONCEPTUAL REPRESENTATION THROUGH HYDROLOGICAL SIMILARITY

The conceptual approach describes rainfall-runoff process through a series of storage elements controlled by mathematical functions. Models that use this approach are often called bucket-type models. Although in principle it is a lumped approach, landscape heterogeneity can be considered by differing parameter values across the model domain, through a concept called hydrological similarity. Based on the principle that many points in a catchment have similar water balance and runoff generation characteristics, they can be grouped in terms of their hydrological similarity, therefore without the need to consider every point separately (Beven, 2012; Flügel, 1997). This concept allows models to account for soil processes in a distributed sense while model structure and related parameters remain lumped at catchment scale (Fenicia et al., 2008).

A strategy to address hydrological similarity is based on the idea of hydrological response units (HRUs). These are, in most cases, combinations of several overlaying maps of landscape characteristics, usually soil and vegetation (Devito et al., 2005; Fan et al., 2015; Flügel, 1997). The resulting HRU map provides a distributed catchment response while the process representation is lumped at the HRU scale. Each unit can have its own structure and/or parameter set. The increasingly available databases of geographical information and ease of manipulating maps on computers has made the use of the HRU approach widely spread (Beven, 2012).

Models of this type include the SWAT model (Arnold et al., 1998), the LISFLOOD model (De Roo et al., 2000) and the MGB model (Collischonn et al., 2007). The definition of HRUs differs widely for different models and applications. In most HRU applications, spatial differences across the landscape are accounted by model parameters, with no modifications in model architecture. Although this allows for some flexibility, the processes remain the same among individual model units, neglecting that different parts of the landscape have different dominant processes (Nijzink et al., 2016).

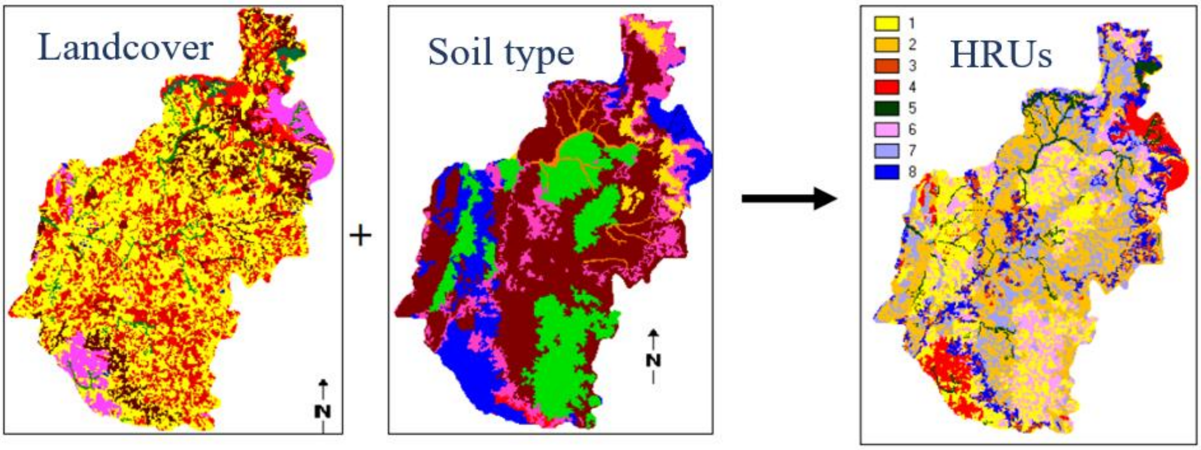

Figure 2 – HRU definition by overlaying maps of land cover and soil type (Collischonn, 2001).

A valuable information that strongly controls hydrological conditions, such as groundwater flux and soil moisture, is topography (Beven and Kirkby, 1979; Moore et al., 1991; Nobre et al., 2011; Sørensen et al., 2006). The partitioning and destination of incoming and outgoing water fluxes are defined by soil moisture conditions, and its spatial distribution (induced by topography) plays important roles in controlling infiltration, evapotranspiration, recharge and runoff generation (Famiglietti et al., 1998; Nobre et al., 2011). Although sometimes used to define HRUs, topography usually remains only implicitly considered by parametrization, as the distribution curve of the soil moisture function can be interpreted as topographic heterogeneity.

The TOPMODEL (Beven and Kirkby, 1979) is a notable example that uses topography to account for hydrological similarity. Spatial heterogeneity is computed by a topographic wetness index (TWI), defined by *ln(a/tan b),* where *a* is the local upslope area draining to a certain point per unit contour length and *tan b* is the local slope gradient. The index is a value that relates to soil moisture conditions of the landscape and it has been widely applied in hydrologic research (Sørensen et al., 2006).

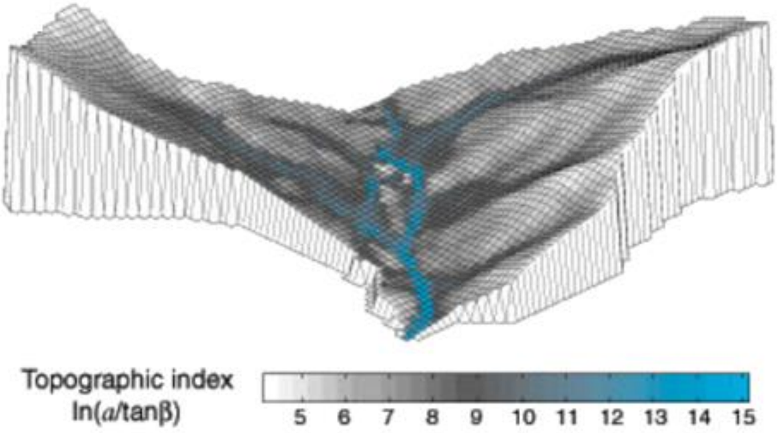

Figure 3 – Representation of the topographic wetness index (TWI). Source: (Beven, 2012).

A recently topography driven conceptual HRU approach is the one suggested by Savenije (2010). The FLEX-Topo uses the conceptualization of the FLEX model (Fenicia et al., 2006, 2008) with a modified framework based on the use of height above nearest drainage (HAND) along with slope to derive landscape classes and dominant runoff mechanism. Its underlying assumption is that different parts of the landscape can be associated with a dominant hydrological flow process (Scherrer and Naef, 2003; Uhlenbrook and Leibundgut, 2002) and that can be constrained by topography.

The HAND algorithm (Nobre et al., 2011; Rennó et al., 2008) gives the vertical distance of a given grid point to the nearest drainage, often called draining potential. Grid points can, then, be classified accordingly to their respective draining gravitational potential, which are inferred to have similar hydrological proprieties that match with soil water and land cover characteristics. It requires a hydrologically coherent DEM (with resolved sinks), computed flow directions and a defined drainage network.

The first idealization of FLEX-Topo was regarded to the conceptual model of the Meuse catchment in Western Europe (Figure 4). Through his perception, Savenije (2010) elaborated a connected system with dominant runoff generation for each landscape element: wetlands (riparian zones) with dominant excess saturation mechanism, hillslopes with subsurface flow mechanism and plateaus with deep percolation to aquifer and hortonian excess infiltration mechanisms. He argues that in each of these three elements, defined by the HAND algorithm and terrain slope, the topography could be related to soils and vegetation through the coevolution of the landscape.

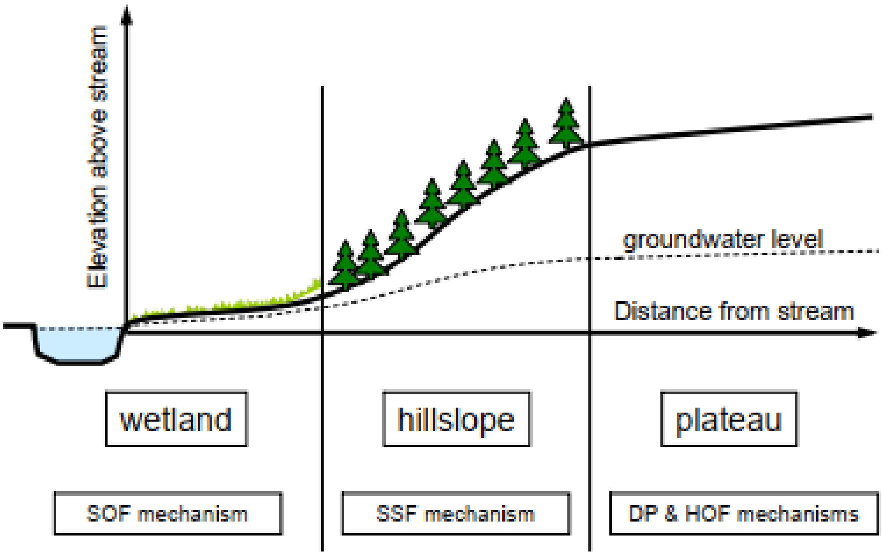

Figure 4 – FLEX-Topo model concept of the Meuse catchment in Western Europe. Sub-systems with different dominant runoff generation mechanisms: saturation excess overland flow (SOF), storage excess sub-surface flow (SSF) evaporation excess deep percolation (DP) and infiltration excess overland flow (HOF). Source: (Savenije, 2010).

The concept of landscape coevolution is not new to hydrological studies. Climate, vegetation, soil and topography have influence on each other’s long-term formation (Sivapalan, 2006; Troch et al., 2013; Wagener et al., 2007). Topography, particularly, can be used as a proxy for soil formation (Behrens et al., 2010; Lin and Zhou, 2008; Park and van de Giesen, 2004; Pelletier and Rasmussen, 2009) and vegetation cover (Fan et al., 2019; Furley, 1999; Nobre et al., 2011; Rennó et al., 2008), as it greatly influences local energy and water budget. Remote sensing allows the widely availability of this information, and the potential of its applications in hydrological sciences is not yet fully explored.

FLEX-Topo model conception tries to explore it by using a powerful tool (HAND) combined with a simple metric (slope). Some applications showed interesting results. Different frameworks of the FLEX model were tested in a 10 000 km² catchment in north-western China and concluded that a topography-driven landscape classification reflected catchment heterogeneity in a more realistic way (Gao et al., 2014). Similarly, different structures were tested to assess model transferability in a tropical savanna region, in Thailand, and the accounting of topography and vegetation in both model structure and calibration provided the best result (Gao et al., 2016).

Gharari et al. (2015) evaluated three model structures with increasing complexity: (a) lumped, (b) parallel structures for wetland and reminder and (c) parallel structures for wetland, hillslope and plateau. Nijzink et al. (2016) used the same methods, but comparing (a) and (c) structures, applied to the mHM model (Kumar et al., 2013; Samaniego et al., 2010). They tested the original model framework and the HRU approach with plateau, hillslope and wetland. Both studies concluded that the incorporation of topography-controlled sub-grid process heterogeneity together with parameter and process constraints improves model performance, particularly in low flows. Such improvement in hydrological consistency can be beneficial for transferring models to other catchments without further calibration, which can help in predicting flows at ungauged catchments.

CONCLUSION

Physically based models have high computational demand and great uncertainty in parameter definition due to scale gaps between the equations used and the model elements. The use of landscape information, such as topography and vegetation, in simpler frameworks can provide valuable insights to fill these gaps, as parameter values can be constrained by physical quantities derived by observation, expert experience and field knowledge. Models that reflect landscape heterogeneity also have considerable potential in applications involving predictions in ungauged basins (PUB) and changing environments. The challenge remains in connecting landscape features to hydrological processes, as theories and field experiments need to be developed from different areas of hydrological knowledge.

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