

Better models are more effectively connected models

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ABSTRACT: Water- and sediment-transfer models are commonly used to explain or predict patterns in the landscape at scales different from those at which observations are available. These patterns are often the result of emergent properties that occur because processes of water and sediment transfer are connected in different ways. Recent advances in geomorphology suggest that it is important to consider, at a specific spatio-temporal scale, the structural connectivity of system properties that control processes, and the functional connectivity resulting from the way those processes operate and evolve through time. We argue that a more careful consideration of how structural and functional connectivity are represented in models should lead to more robust models that are appropriate for the scale of application and provide results that can be upscaled. This approach is necessary because, notwithstanding the significant advances in computer power in recent years, many geomorphic models are still unable to represent the landscape in sufficient detail to allow all connectivity to emerge. It is important to go beyond the simple representation of structural connectivity elements and allow the dynamics of processes to be represented, for example by using a connectivity function. This commentary aims to show how a better representation of connectivity in models can be achieved, by considering the sorts of landscape features present, and whether these features can be represented explicitly in the model spatial structure, or must be represented implicitly at the subgrid scale. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: structural connectivity; functional connectivity; water and sediment transfers; modelling; subgrid processes

Introduction

The catchment provides a versatile domain for understanding geomorphic and hydrologic processes at a range of spatial and temporal scales. However, interactions, feedbacks and complex behaviour within catchments produce emergent properties which make it difficult to translate understanding between different scales, both in estimating larger-scale properties from smaller-scale observations (upscaling) or smaller-scale patterns from larger-scale outcomes (downscaling). Numerical modelling is often used as a tool to understand catchments and to attempt to overcome these scaling difficulties, either by supplementing observations with model results for unmeasured variables or at unmeasured locations (Croke et al. 2013; Nunes et al. 2009; Stieglitz et al. 2003), or for designing and testing different conceptual models of catchment

behaviour (Hoffmann 2015; Van Nieuwenhuyse et al. 2011). To do so, models should be able to reproduce both the patterns and the linkages of water and sediment fluxes within the catchment(s) under simulation – herein referred to as landscape connectivity. Recent theoretical advances have improved the understanding of connectivity and the description of associated processes (Bracken et al. 2013, 2015), and these advances can be used to create better hydrologic and geomorphic catchment models by improving the way in which they represent landscape connectivity. However, achieving these improvements is far from straightforward; so far, there is no clear framework to guide how connectivity should be represented inside model components.

We argue that the path to building better models is to build more effectively connected models, i.e. models which better represent fluxes of water and sediment through space, by

better representing connectivity within and between its fundamental spatial units. The aim of this commentary is to suggest some ways in which a better representation of connectivity can be achieved. We discuss improvements in parameterizing connectivity, and propose using the scale of the fundamental modelling unit to select an appropriate combination between parameterized and emergent connectivity modelling approaches.

Representing landscape connectivity

The representation of connectivity in models must first recognize the difference between structural and functional connectivity. The former reflects static properties of the system at a given timescale, while the latter represents the dynamic behaviour of the system at that timescale (Turnbull et al. 2008; Wainwright et al. 2011; With et al. 1997; Wu and David 2002). The actual separation between structural and functional connectivity depends on the timescale of the analysis, as functional connectivity may act to reorganize the system and change structural connectivity at longer timescales, which must also be considered in model design (Wainwright et al. 2011). Once the timescale for a given model is set, functional connectivity will be represented by the water and material flows simulated by the model, while structural connectivity will be represented by the model's underlying spatial structure. Structural connectivity can be conceptualized as a spatial pattern of interconnected elements, linking the (microscopic) scale of the fundamental units via their basic links to neighbouring units, and the (macroscopic) scale at which the overall behaviour is considered: in this case, the catchment.

The fundamental unit is the lowest level within this spatial hierarchy, i.e. the measurement unit of the entity of interest. In hydrology, the fundamental unit is traditionally defined based on structural characteristics of hydrological networks, such as the channel reach or sub-catchment, but could equally well be defined based on the scale of a process or, for convenience, as a single cell (pixel). Defining the appropriate scale of the fundamental unit should depend on the scale at which it is conceptually robust to work for a given application. However, typically, the fundamental unit is defined based on the scale at which measurements of parameters or processes

are made, or at which data are available (often limited by access to DTMs), which does not necessarily equate to the scale(s) at which it is conceptually robust to work (see Grieve et al. 2016). This mismatch between the theoretical and the actual scale of the fundamental unit is a common limitation when designing the spatial structure of models.

Links between fundamental units define the directionality and magnitude of transfers of water or materials among them. In catchment models, these links create a network for the transfers throughout the system from which, ultimately, the larger scale behaviour is determined (Heckmann and Schwanghart 2013). The properties of each basic link can be represented as continuous (i.e. based on a process, such as the water flux through a stream reach) or discretized (i.e. classifying the property as high, intermediate, low, null) or even binary (i.e. on/off) (Larsen et al. 2012). The scale at which fundamental units are represented will affect how links can be represented, and therefore limitations in defining units will affect the structural link network.

Addressing connectivity in models

Distributed hydrological and sediment-transport models have been developed over the last few decades to take advantage of increased process understanding and availability of spatio-temporal data. To implement the concepts of landscape connectivity in these models (Bracken and Croke 2007; Lexartza-Artza and Wainwright 2009; Western et al. 2001), a range of approaches can be adopted between two extremes (Figure 1):

- (i) A fully explicit approach, in which all system properties and processes considered relevant are explicitly taken into account, and where connectivity is an emergent property from model results – in other words where basic links are considered explicitly; for instance, high-resolution spatially distributed models.
- (ii) An implicit approach, in which some or all connectivity-relevant links and properties are represented through proxies, and processes have been parameterized to include connectivity; for instance, lumped catchment models.
- (iii) Hybrid approaches, standing in-between these extremes, are also possible; for instance, large watershed models

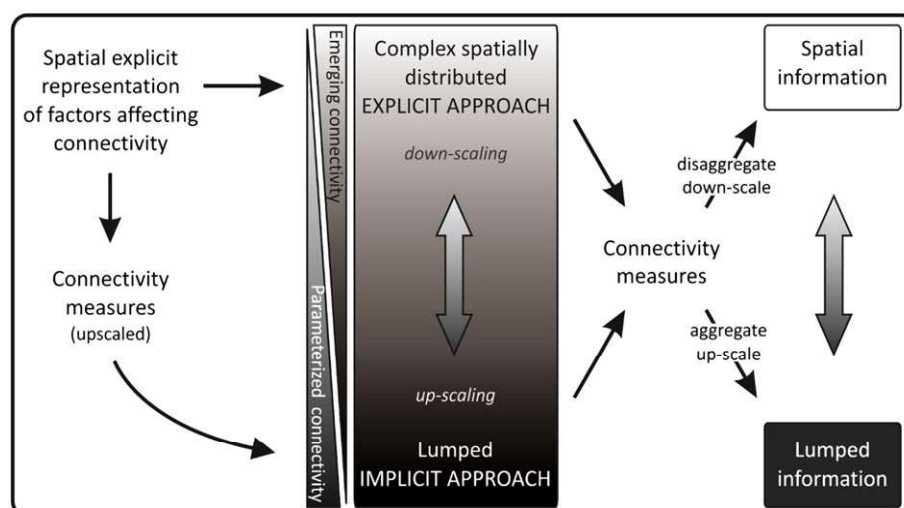


Figure 1. Schematic overview of the different representations of landscape connectivity in different modelling approaches. [Colour figure can be viewed at wileyonlinelibrary.com]

linking lumped models of individual catchments to a distributed model of the stream network.

A large number of spatially distributed hydrological and erosion models seek to represent the connectivity of most processes explicitly, by attempting to appropriately define the fundamental unit and their links (Cerdan *et al.* 2002; De Roo *et al.* 1996; Nunes *et al.* 2005; Wainwright *et al.* 2008), providing a physically based description of the link (Finger *et al.* 2011) and, in some cases, including the dynamic evolution of links due to micro- or macro-topographic changes (Ciampalini *et al.* 2012; Fiener *et al.* 2008; Schoorl *et al.* 2002). However, even in the most complicated of these models, connectivity-relevant properties and processes are only in part represented explicitly, due to: (i) the incomplete understanding or coding of processes; (ii) model resolution and computational considerations; and (iii) theoretical limitations to model completeness (Mulligan and Wainwright 2013a; Rosenbluth and Wiener 1945). Model resolution is, in fact, often too coarse to represent the system in such a way that connectivity can emerge.

Furthermore, links between fundamental units are often hidden in effective parameters (i.e. model parameters which are different from the equivalent measurement to account for a process which the model structure does not represent), and thus, links do not dynamically interact with connectivity-related processes. A typical case in many runoff models is where random or orientated surface roughness is parameterized (e.g. as static Manning's n or roughness height due to tillage operations) without any process interaction (Fiener *et al.* 2011; Smith *et al.* 2007; Williams 1970). These problems may be hidden by the disparity in the scales of the fundamental unit (usually the raster cell) and of the field observation used to evaluate the model (often a catchment outflow), but they are important in the simulation of spatial patterns.

Problems can be circumvented by using the implicit approach: representing fine-scale structures and processes within coarser-scale modelling approaches, which helps to improve representations of landscape connectivity, and at a lower cost in terms of data input and computational requirements but at the expense of some loss of accuracy compared with a fully explicit model. This approach is usually adopted by lumped and semi-distributed models used on larger scales, i.e. where the fundamental unit is defined at a much coarser spatial scale (e.g. in SWAT; Arnold and Fohrer 2005; see discussion in Mulligan and Wainwright 2013b). However, in the implicit approach, connectivity is also often represented by effective parameters with little dynamic evolution or interaction between processes, limiting the simulation of emergent behaviour at the catchment scale. For example, connectivity is implicit in the use of soil moisture to select different rainfall-runoff response functions such as with the Curve Number approach (Garen and Moore 2005), or in the use of a single value to represent sediment transfer between units, either a fixed percentage (Watem-Sedem, Van Oost *et al.* 2000) or a fixed mass (STREAM, Cerdan *et al.* 2002), even though these values may, in fact, evolve through space and time.

What is common to many of these approaches is the representation of functional connectivity as a static property or, at best, one with limited changes. Stochastic approaches have been proposed where deterministic links are replaced by all units having a probability of being linked to others (see Hütt *et al.* 2012, for a non-geomorphologic example), but they still do not overcome the inherently static nature in which the system is represented. Models that attempt to simulate the temporal behaviour of systems cannot represent the evolutionary

behaviour of those systems correctly if they do not capture the dynamics of functional connectivity in some way. One approach to achieve this dynamic representation of connectivity would be to use a connectivity function.

From functional connectivity to connectivity functions

To produce a connectivity function, one must first start with an explicit representation of fundamental units; then, once the emergent behaviour of these links has been described, a simple and sound functional relationship can be derived to represent implicitly the interactions among individual links. A landscape-connectivity function will reflect the connectivity in overland flow or sediment transfer within the unit. Percolation theory provides an example of a conceptual framework in which these relationships can be derived from first principles (Berkowitz and Ewing 1998; Darboux *et al.* 2002; Harel and Mouche 2014), although more often the relationships are derived by the confrontation of empirical data with transport equations of varying degrees of complexity.

A connectivity function can, in principle, be represented by a binary or continuous approach. A continuous definition does not necessarily lead to a better assessment of connectivity and it is even usual for a connectivity evaluation procedure to start with the binarization of the continuous values of individual links (Souchère *et al.* 1998). A simple example of a connectivity-based binary switch at a relatively small scale (DTM grid cell) is when a decision is made regarding flow direction in the presence of orientated roughness whenever the orientation of tillage-induced roughness does not coincide with slope aspect (Souchère *et al.* 1998; Takken *et al.* 2001). In this case, the binary switch does not affect whether or not two contiguous cells are connected, but it governs the directionality of the flow, i.e. it controls which neighbouring cell becomes connected to the source cell. Other examples of binary connectivity switches in hydrological models include the use of the maximum depression storage as a threshold to transfer flow from one modelling unit to one or more neighbours (Singh and Frevert 2002), and the so-called 'bucket models' in which water is transferred from one soil layer to the next only after the moisture content reaches field capacity (Walker and Zhang 2001).

Alternatively, a continuous function may be used to describe connectivity whereby units are connected via links with varying levels of connectivity. Taking the examples given above, Razafison *et al.* (2012) introduced a non-binary approach to determine water flow in the topographic or the tillage direction based on an anisotropic friction coefficient; and the LISEM model replaces the maximum depression storage approach by a continuous function governing the rate of water transfer as a function of the degree of filling of the depression storage (De Roo *et al.* 1996). Other examples of such continuous switches are the recent use of the 'porosity concept' to regulate the amount and cross-section of flow between adjacent cells (Lane *et al.* 2004; McMillan and Brasington 2007).

Antoine *et al.* (2009) developed a more complex approach to express sub-grid water connectivity as a function of the level of depression storage filled, the relative surface connection function (RSCf). Depressions and flow-paths within a given model cell are explicitly simulated from rainfall using a very high resolution (10 mm) DTM. The RSCf can be combined with a weighted surface procedure to generate realistic hydrographs of elementary units (Antoine *et al.* 2011). Peñuela *et al.* (2015) replaced the need for a high-resolution DTM with a three-point

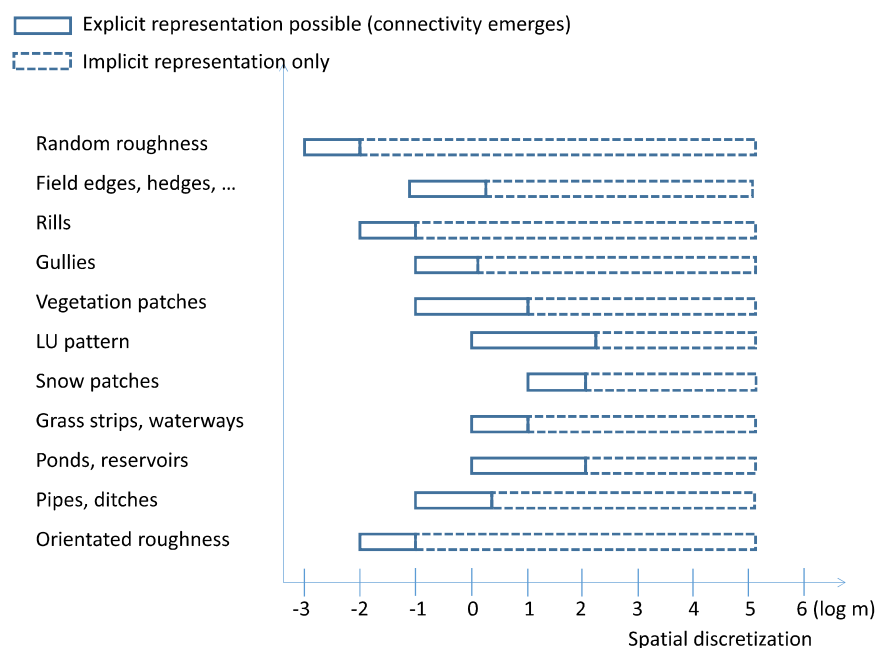


Figure 2. Schematic representation of scales at which certain landscape features that are influential in terms of water or sediment connectivity are resolved explicitly or implicitly in environmental models. [Colour figure can be viewed at wileyonlinelibrary.com]

parameterization estimated from slope and structural terrain information for random roughness, which allows application of this method at the watershed scale.

Building more effectively connected models

Models can effectively integrate connectivity by using connectivity functions. These functions should be selected to represent the fundamental unit for which the model was designed, which can range from small to large scales, e.g. from single DTM grid cells and fields to entire watersheds. Figure 2 provides an initial assessment of the likely scales at which connectivity could be included in model design, and whether the representation of connectivity should be explicit, i.e. allowed to emerge from existing connectivity links; or implicit, i.e. through connectivity functions.

A schematic representation such as this can help decide the appropriate resolution of application for a given model, based on the processes that are represented implicitly. For example, commonly used spatially distributed models such as LISEM (De Roo et al. 1996) or LandSoil (Ciampalini et al. 2012) are typically applied with spatial resolutions between 1 and 10 m. While these relatively fine resolutions should allow them to represent most connectivity processes explicitly, implicit solutions should be found to address, for example, connectivity due to roughness and rills. Moreover, the application of these models with larger-resolutions DTMs such as global datasets with resolutions between 30 and 90 m would stretch their capacities, as it would be difficult for the connectivity effects of vegetation patches, field edges or gullies to be explicitly represented. Past approaches have tried to address this issue using sub-grid scale parameterization (Zhang et al. 2002), but progress is now needed to integrate sub-grid scale processes in models using connectivity functions to take advantage of the opportunities offered by these datasets.

Model development is always a trade-off between inclusion of detail and parsimony of representation. By considering why parameters may be appropriate at different scales, and how

connectivity functions can represent linkages between different scales, we suggest that more robust models can be designed that will require less (or no) empirical calibration, and thus underpin their physical basis and potential for extrapolation. The use of such linkages also supports process based up- or downscaling, and can thus aid in model evaluation and testing where data are only available at very different scales from model implementation. While the increasing availability of high resolution topographic data (e.g. from TLS and UAVs: Ouedraogo et al. 2014; Pineux et al. 2017) means that models could be applied at very high spatial resolutions to account for connectivity explicitly, computational tractability means that it is unlikely that direct advantage can be taken of these data for some time to come. By using these data in the definitions of connectivity functions, direct advantage can be taken of these data immediately, especially if connectivity links across different scales can be defined *a priori*. More research is required to define connectivity functions that can be applied at a wide range of scales and in relation to different processes, and in particular to define the feedbacks between functional and structural connectivity at different scales.

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