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## Better models are more effectively connected models

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## 4 Better models are more effectively connected models

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22ABSTRACT: Water- and sediment-transfer models are commonly used to explain or  
23predict patterns in the landscape at scales different from those at which observations  
24are available. These patterns are often the result of emergent properties that occur  
25because processes of water and sediment transfer are connected in different ways.  
26Recent advances in geomorphology suggest that it is important to consider, at a  
27specific spatio-temporal scale, the structural connectivity of system properties that  
28control processes, and the functional connectivity resulting from the way those  
29processes operate and evolve through time. We argue that a more careful  
30consideration of how structural and functional connectivity are represented in models  
31should lead to more robust models that are appropriate for the scale of application  
32and provide results that can be upscaled. This approach is necessary because,  
33notwithstanding the significant advances in computer power in recent years, many  
34geomorphic models are still unable to represent the landscape in sufficient detail to  
35allow all connectivity to emerge. It is important to go beyond the simple  
36representation of structural connectivity elements and allow the dynamics of  
37processes to be represented, for example by using a connectivity function. This  
38commentary aims to show how a better representation of connectivity in models can  
39be achieved, by considering the sorts of landscape features present, and whether  
40these features can be represented explicitly in the model spatial structure, or must  
41be represented implicitly at the subgrid scale.

42

43KEYWORDS: structural connectivity, functional connectivity, water and sediment  
44transfers, modelling, subgrid processes

45

## 46Introduction

47The catchment provides a versatile domain for understanding geomorphic and  
48hydrologic processes at a range of spatial and temporal scales. However,  
49interactions, feedbacks and complex behaviour within catchments produce emergent  
50properties which make it difficult to translate understanding between different scales,  
51both in estimating larger-scale properties from smaller-scale observations  
52(upscaling) or smaller-scale patterns from larger-scale outcomes (downscaling).  
53Numerical modelling is often used as a tool to understand catchments and to attempt  
54to overcome these scaling difficulties, either by supplementing observations with  
55model results for unmeasured variables or at unmeasured locations (e.g. Stieglitz *et*  
56*al.*, 2003; Nunes *et al.*, 2009; Croke *et al.*, 2013), or for designing and testing  
57different conceptual models of catchment behaviour (e.g. Van Nieuwenhuysse *et al.*,  
582011; Hoffmann, 2015). To do so, models should be able to reproduce both the  
59patterns and the linkages of water and sediment fluxes within the catchment(s) under  
60simulation – herein referred to as landscape connectivity. Recent theoretical  
61advances have improved the understanding of connectivity and the description of  
62associated processes (Bracken *et al.*, 2013, 2015), and these advances can be used  
63to create better hydrologic and geomorphic catchment models by improving the way  
64in which they represent landscape connectivity. However, achieving these  
65improvements is far from straightforward; so far, there is no clear framework to guide  
66how connectivity should be represented inside model components.

67We argue that the path to building better models is to build more effectively  
68connected models, i.e. models which better represent fluxes of water and sediment  
69through space, by better representing connectivity within and between its  
70fundamental spatial units. The aim of this commentary is to suggest some ways in  
71which a better representation of connectivity can be achieved. We discuss  
72improvements in parameterizing connectivity, and propose using the scale of the  
73fundamental modelling unit to select an appropriate combination between  
74parameterized and emergent connectivity modelling approaches.

75

## 76 **Representing landscape connectivity**

77 The representation of connectivity in models must first recognize the difference  
78 between structural and functional connectivity. The former reflects static properties of  
79 the system at a given timescale, while the latter represents the dynamic behaviour of  
80 the system at that timescale (Turnbull *et al.*, 2008; Wainwright *et al.*, 2011; With *et*  
81 *al.*, 1997; Wu and David, 2002). The actual separation between structural and  
82 functional connectivity depends on the timescale of the analysis, as functional  
83 connectivity may act to reorganize the system and change structural connectivity at  
84 longer timescales, which must also be considered in model design (Wainwright *et al.*,  
85 2011). Once the timescale for a given model is set, functional connectivity will be  
86 represented by the water and material flows simulated by the model, while structural  
87 connectivity will be represented by the model's underlying spatial structure.  
88 Structural connectivity can be conceptualized as a spatial pattern of interconnected  
89 elements, linking the (microscopic) scale of the fundamental units via their basic links  
90 to neighbouring units, and the (macroscopic) scale at which the overall behaviour is  
91 considered: in this case, the catchment.

92 The fundamental unit is the lowest level within this spatial hierarchy, i.e. the  
93 measurement unit of the entity of interest. In hydrology, the fundamental unit is  
94 traditionally defined based on structural characteristics of hydrological networks,  
95 such as the channel reach or sub-catchment, but could equally well be defined  
96 based on the scale of a process or, for convenience, as a single cell (pixel). Defining  
97 the appropriate scale of the fundamental unit should depend on the scale at which it  
98 is conceptually robust to work for a given application. However, typically, the  
99 fundamental unit is defined based on the scale at which measurements of  
100 parameters or processes are made, or at which data are available (often limited by  
101 access to DTMs), which does not necessarily equate to the scale(s) at which it is  
102 conceptually robust to work (see Grieve *et al.*, 2016). This mismatch between the  
103 theoretical and the actual scale of the fundamental unit is a common limitation when  
104 designing the spatial structure of models.

105 Links between fundamental units define the directionality and magnitude of transfers  
106 of water or materials among them. In catchment models, these links create a

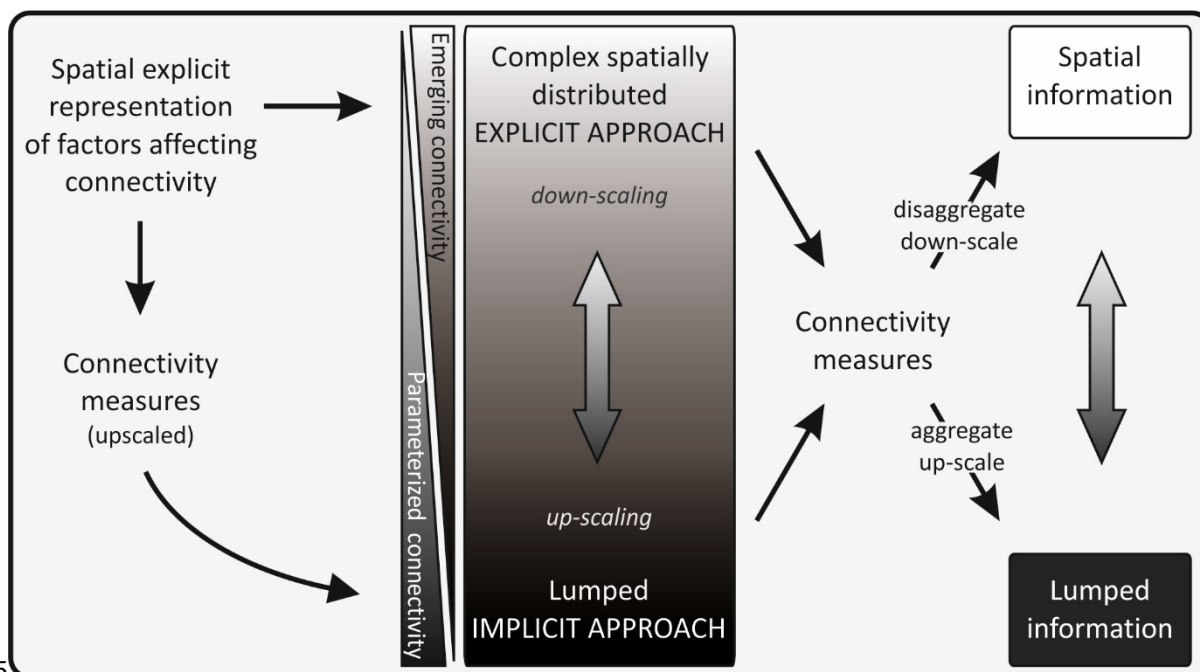
107network for the transfers throughout the system from which, ultimately, the larger  
108scale behaviour is determined (see Heckmann and Schwanghart, 2013). The  
109properties of each basic link can be represented as continuous (i.e. based on a  
110process, such as the water flux through a stream reach) or discretized (i.e.  
111classifying the property as high, intermediate, low, null) or even binary (i.e. on/off)  
112(e.g. Larsen *et al.*, 2012). The scale at which fundamental units are represented will  
113affect how links can be represented, and therefore limitations in defining units will  
114affect the structural link network.

115

### 116**Addressing connectivity in models**

117Distributed hydrological and sediment-transport models have been developed over  
118the last few decades to take advantage of increased process understanding and  
119availability of spatio-temporal data. To implement the concepts of landscape  
120connectivity in these models (e.g. Bracken and Croke, 2007; Lexartza-Artza and  
121Wainwright, 2009; Western *et al.*, 2001), a range of approaches can be adopted  
122between two extremes (Figure 1):

- 123 (i) A fully explicit approach, in which all system properties and processes  
124 considered relevant are explicitly taken into account, and where  
125 connectivity is an emergent property from model results – in other words  
126 where basic links are considered explicitly; for instance, high-resolution  
127 spatially distributed models.
- 128 (ii) An implicit approach, in which some or all connectivity-relevant links and  
129 properties are represented through proxies, and processes have been  
130 parameterized to include connectivity; for instance, lumped catchment  
131 models.
- 132 (iii) Hybrid approaches, standing in-between these extremes, are also  
133 possible; for instance, large watershed models linking lumped models of  
134 individual catchments to a distributed model of the stream network.



135

136 Figure 1: Schematic overview of the different representations of landscape  
 137 connectivity in different modelling approaches.

138 A large number of spatially distributed hydrological and erosion models seek to  
 139 represent the connectivity of most processes explicitly, by attempting to appropriately  
 140 define the fundamental unit and their links (e.g. De Roo *et al.*, 1996; Cerdan *et al.*,  
 141 2002; Nunes *et al.*, 2005; Wainwright *et al.*, 2008), providing a physically based  
 142 description of the link (e.g. Finger *et al.*, 2011) and, in some cases, including the  
 143 dynamic evolution of links due to micro- or macro-topographic changes (e.g. School  
 144 *et al.*, 2002; Fiener *et al.*, 2008; Ciampalini *et al.*, 2012). However, even in the most  
 145 complicated of these models, connectivity-relevant properties and processes are  
 146 only in part represented explicitly, due to (i) the incomplete understanding or coding  
 147 of processes, (ii) model resolution and computational considerations, and (iii)  
 148 theoretical limitations to model completeness (Mulligan and Wainwright, 2013a;  
 149 Rosenblueth and Wiener, 1945). Model resolution is, in fact, often too coarse to  
 150 represent the system in such a way that connectivity can emerge.

151 Furthermore, links between fundamental units are often hidden in effective  
 152 parameters (i.e. model parameters which are different from the equivalent  
 153 measurement to account for a process which the model structure does not  
 154 represent), and thus, links do not dynamically interact with connectivity-related  
 155 processes. A typical case in many runoff models is where random or orientated

156 surface roughness is parameterized (e.g. as static Manning's  $n$  or roughness height  
157 due to tillage operations) without any process interaction (e.g. Smith *et al.* 2007;  
158 Williams, 1970; Fiener *et al.*, 2008). These problems may be hidden by the disparity  
159 in the scales of the fundamental unit (usually the raster cell) and of the field  
160 observation used to evaluate the model (often a catchment outflow), but they are  
161 important in the simulation of spatial patterns.

162 Problems can be circumvented by using the implicit approach: representing fine-  
163 scale structures and processes within coarser-scale modelling approaches, which  
164 helps to improve representations of landscape connectivity, and at a lesser cost in  
165 terms of data input and computational requirements but at the expense of some loss  
166 of accuracy compared to a fully explicit model. This approach is usually adopted by  
167 lumped and semi-distributed models used on larger scales, i.e. where the  
168 fundamental unit is defined at a much coarser spatial scale (e.g. in SWAT; Arnold  
169 and Fohrer, 2005; see discussion in Mulligan and Wainwright 2013b). However, in  
170 the implicit approach, connectivity is also often represented by effective parameters  
171 with little dynamic evolution or interaction between processes, limiting the simulation  
172 of emergent behaviour at the catchment scale. For example, connectivity is implicit in  
173 the use of soil moisture to select different rainfall-runoff response functions such as  
174 with the Curve Number approach (Garen and Moore, 2005), or in the use of a single  
175 value to represent sediment transfer between units, either a fixed percentage (e.g.  
176 Watem-Sedem, Van Oost *et al.*, 2000) or a fixed mass (e.g. STREAM, Cerdan *et al.*,  
177 2002), even though these values may, in fact, evolve through space and time.

178 What is common to many of these approaches is the representation of functional  
179 connectivity as a static property or, at best, one with limited changes. Stochastic  
180 approaches have been proposed where deterministic links are replaced by all units  
181 having a probability of being linked to others (see Hütt *et al.*, 2012, for a non-  
182 geomorphologic example), but they still do not overcome the inherently static nature  
183 in which the system is represented. Models that attempt to simulate the temporal  
184 behaviour of systems cannot represent the evolutionary behaviour of those systems  
185 correctly if they do not capture the dynamics of functional connectivity in some way.  
186 One approach to achieve this dynamic representation of connectivity would be to use  
187 a connectivity function.



### 189 **From functional connectivity to connectivity functions**

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

200 A connectivity function can, in principle, be represented by a binary or continuous  
201 approach. A continuous definition does not necessarily lead to a better assessment  
202 of connectivity and it is even usual for a connectivity evaluation procedure to start  
203 with the binarization of the continuous values of individual links (e.g. Souchère *et al.*,  
204 1998). A simple example of a connectivity-based binary switch at a relatively small  
205 scale (DTM grid cell) is when a decision is made regarding flow direction in the  
206 presence of orientated roughness whenever the orientation of tillage-induced  
207 roughness does not coincide with slope aspect (Souchère *et al.*, 1998; Takken *et al.*,  
208 2001). In this case, the binary switch does not affect whether or not two contiguous  
209 cells are connected, but it governs the directionality of the flow, i.e. it controls which  
210 neighbouring cell gets connected to the source cell. Other examples of binary  
211 connectivity switches in hydrological models include the use of the maximum  
212 depression storage as a threshold to transfer flow from one modelling unit to one or  
213 more neighbours (Singh and Frevert, 2002), and the so-called “bucket models” in  
214 which water is transferred from one soil layer to the next only after the moisture  
215 content reaches field capacity (Walker and Zhang, 2001).

216 Alternatively, a continuous function may be used to describe connectivity whereby  
217 units are connected via links with varying levels of connectivity. Taking the examples  
218 given above, Razafison *et al.* (2012) introduced a non-binary approach to determine

219water flow in the topographic or the tillage direction based on an anisotropic friction  
220coefficient; and the LISEM model replaces the maximum depression storage  
221approach by a continuous function governing the rate of water transfer as a function  
222of the degree of filling of the depression storage (De Roo *et al.*, 1996). Other  
223examples of such continuous switches are the recent use of the “porosity concept” to  
224regulate the amount and cross section of flow between adjacent cells (Lane *et al.*,  
2252004; McMillan and Brasington, 2007).

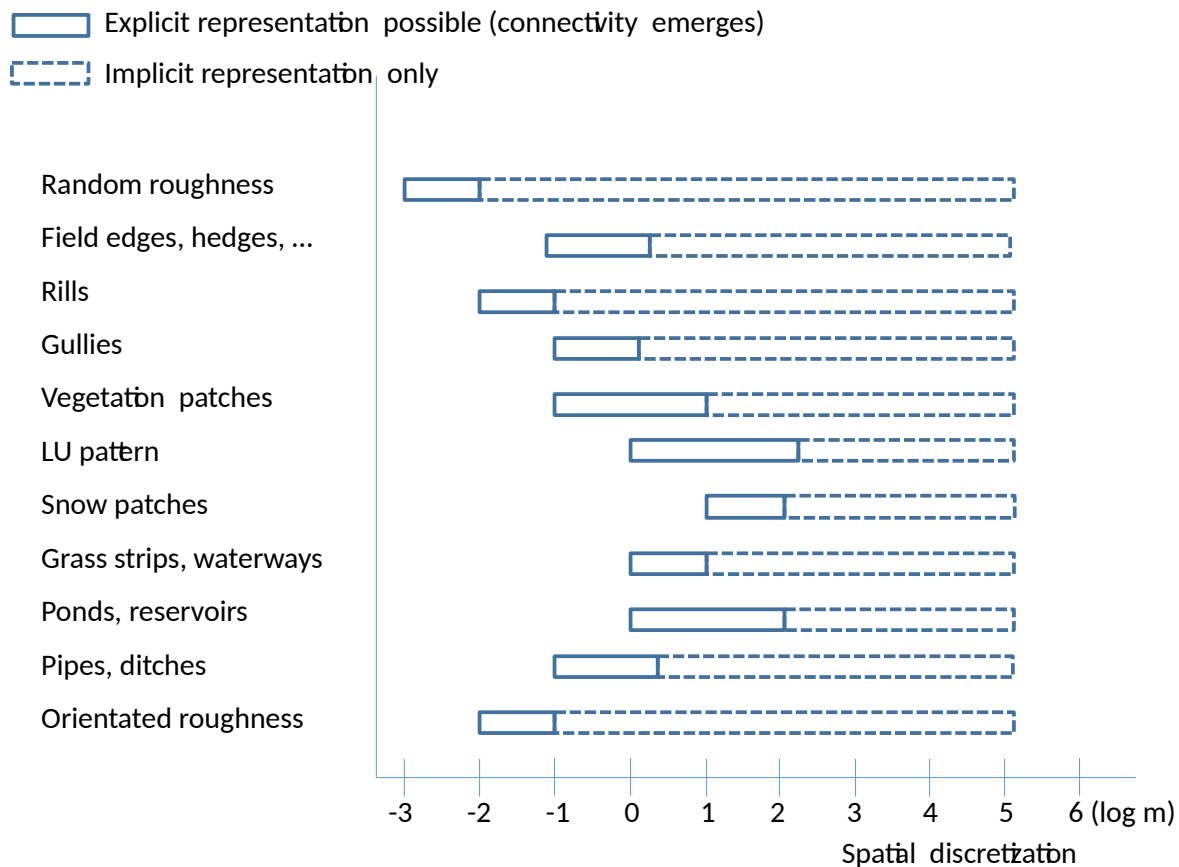
226Antoine *et al.* (1999) developed a more complex approach to express sub-grid water  
227connectivity as a function of the level of depression storage filled, the Relative  
228Surface Connection function (RSCf). Depressions and flow-paths within a given  
229model cell are explicitly simulated from rainfall using a very high resolution (10-mm)  
230DTM. The RSCf can be combined with a weighted surface procedure to generate  
231realistic hydrographs of elementary units (Antoine *et al.*, 2011). Peñuela *et al.* (2015)  
232replaced the need of a high-resolution DTM with a three-point parameterization  
233estimated from slope and structural terrain information for random roughness, which  
234allows the application of this method at the watershed scale.

235

### 236 **Building more effectively connected models**

237Models can effectively integrate connectivity by using connectivity functions. These  
238functions should be selected to represent the fundamental unit for which the model  
239was designed, which can range from small to large scales, e.g. from single DTM grid  
240cells and fields to entire watersheds. Figure 2 provides an initial assessment of the  
241likely scales at which connectivity could be included in model design, and whether  
242the representation of connectivity should be explicit, i.e. allowed to emerge from  
243existing connectivity links; or implicit, i.e. through connectivity functions.

244



245

246 *Figure 2: Schematic representation of scales at which certain landscape features*  
 247 *that are influential in terms of water or sediment connectivity are resolved explicitly*  
 248 *or implicitly in environmental models.*

249

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

262now needed to integrate sub-grid scale processes in models using connectivity  
263functions to take advantage of the opportunities offered by these datasets.

264Model development is always a trade-off between inclusion of detail and parsimony  
265of representation. By considering why parameters may be appropriate at different  
266scales, and how connectivity functions can represent linkages between different  
267scales, we suggest that more robust models can be designed that will require less  
268(or no) empirical calibration, and thus underpin their physical basis and potential for  
269extrapolation. The use of such linkages also supports process based up- or  
270downscaling, and can thus aid in model evaluation and testing where data are only  
271available at very different scales from model implementation. While the increasing  
272availability of high resolution topographic data (e.g. from TLS and UAVs: Ouedraogo  
273*et al.*, 2014; Pineux *et al.*, 2017) means that models could be applied at very high  
274spatial resolutions to account for connectivity explicitly, computational tractability  
275means that it is unlikely that direct advantage can be taken of these data for some  
276time to come. By using these data in the definitions of connectivity functions, direct  
277advantage can be taken of these data immediately, especially if connectivity links  
278across different scales can be defined *a priori*. More research is required to define  
279connectivity functions that can be applied at a wide range of scales and in relation to  
280different processes, and in particular to define the feedbacks between functional and  
281structural connectivity at different scales.

282

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