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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

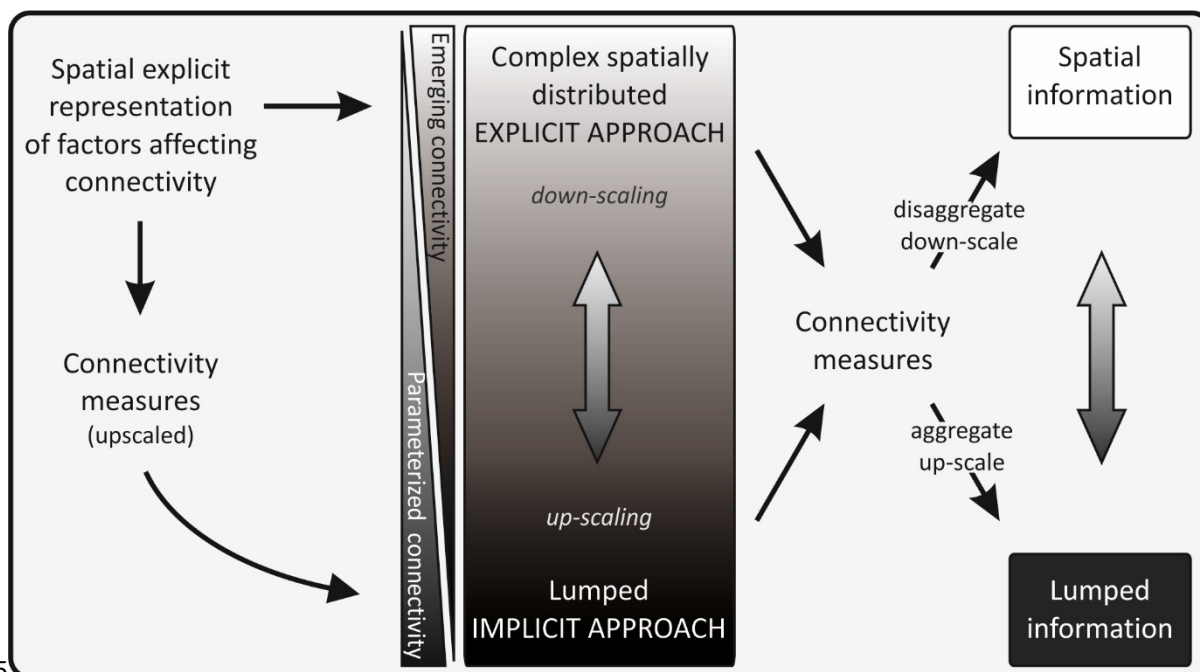
107network for the transfers throughout the system from which, ultimately, the larger
108scale behaviour is determined (see Heckmann and Schwanghart, 2013). The
109properties of each basic link can be represented as continuous (i.e. based on a
110process, such as the water flux through a stream reach) 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).

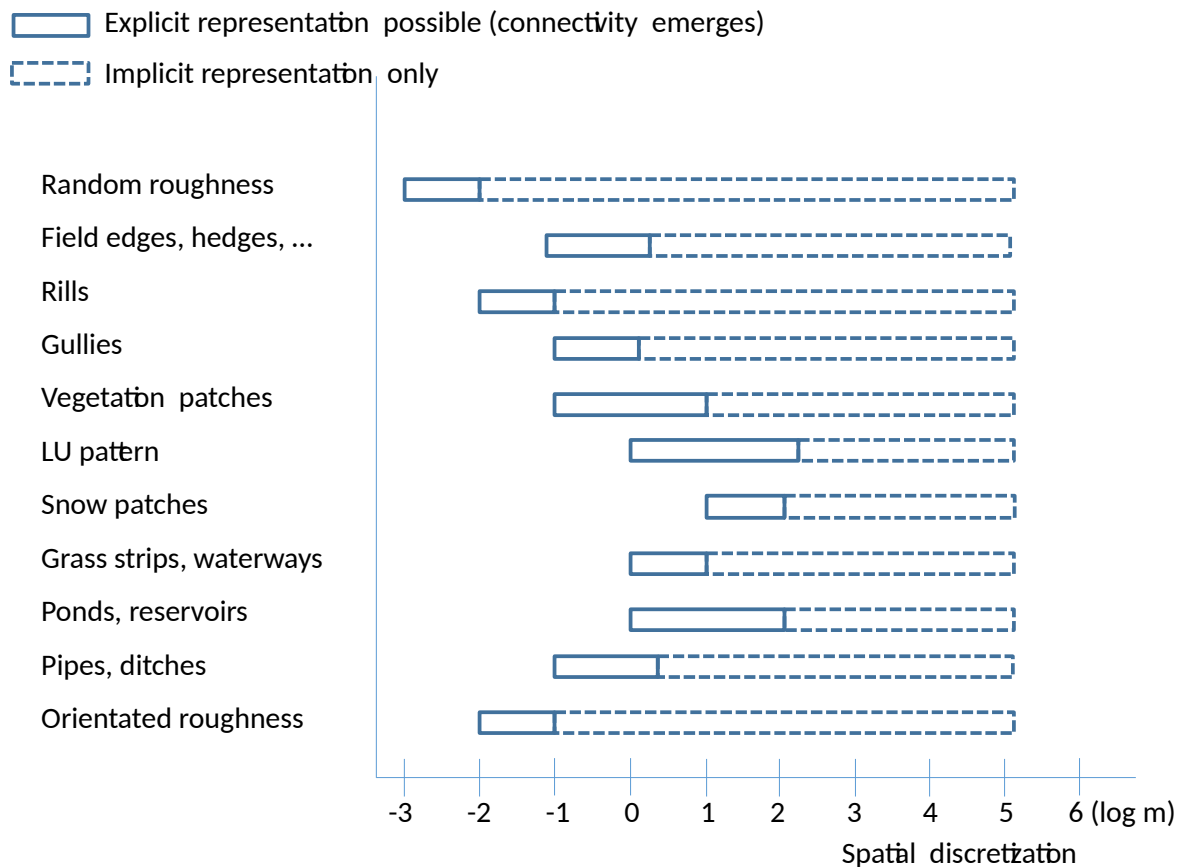
226Antoine *et al.* (1999) developed a more complex approach to express sub-grid water
227connectivity as a function of the level of depression storage filled, the Relative
228Surface Connection function (RSCf). Depressions and flow-paths within a given
229model cell are explicitly simulated from rainfall 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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