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Title

The geomorphic cell: a basis for studying connectivity

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Abstract (max. 300 words)

Any attempt to measure connectivity within a system requires a set of entities to be defined that permit the connectivity amongst them to be quantified. Here we propose the geomorphic cell as such an entity. We provide a means to identify these cells, define a terminology for describing cell state, and identify the pathways of connections (connecteins) to and from cells. We conceptualize the geomorphic cell as being a three-dimensional body of the geomorphosphere, which is delimited from neighboring cells and neighboring spheres by different types of boundary. Vertically, the upper boundary of a geomorphic cell is defined by the atmosphere, while the lower boundary is generally formed by the bedrock layer of the lithosphere. Laterally, geomorphic cells are delimited from neighbouring cells with a change in

environmental characteristics that determine hydro-geomorphic boundary conditions (e.g. geology, soils, topography and/or vegetation).

Keywords
Connectivity; Fundamental unit; Landscape structure and function; Complexity

Background

In recent years there has been a growing body of research into how the elements of complex systems are related to each other. This body of research, termed connectivity science, comprises conceptual models, statistical approaches and mathematical theories, and has led to new insights in fields as diverse as neuroscience, ecology and social science. Geomorphology has also been swept up into this burst of activity, with special issues on connectivity being produced by both Earth Surface Processes and Landforms (in 2014) and by Geomorphology (in 2016), and sessions on the topic at the EGU co-organised by the Geomorphology Division every year since 2012. However, the new insights that have characterized the applications of connectivity science in other disciplines (e.g. Travers and Milgram, 1969, Honey et al., 2009; Tero et al., 2010) appear to have eluded geomorphology. Nonetheless, there have been a number of case studies in which variable responses of geomorphic systems to perturbations have been 'explained' with reference to ideas of connectivity (e.g. Hooke, 2006; Ali et al., 2014; Puttock et al., 2014), and a number of papers exploring connectivity ideas and advocating their application to geomorphology (e.g. Brierley et al., 2006; Fryirs et al., 2007; Lexartza-Artza and Wainwright, 2009; Wainwright et al., 2011; Fryirs, 2013; Bracken et al., 2015; Poeppl et al., 2017). Finally, and of particular interest in the context of this Commentary, have been the papers that have sought to provide means to measure and describe geomorphic connectivity.

Any attempt to measure connectivity within a system requires a set of entities to be defined that permit the connectivity amongst them to be quantified (termed Fundamental Units FUs). Such FUs need to be meaningful within the system of study. What is meaningful will almost certainly be a function of the temporal and spatial scales of the investigation and of the available measurement techniques. Without prior consideration of the meaningfulness of the FUs it is unlikely that examination of their connectivity will yield useful insights into the characteristics and behaviour of the system under study. In neuroscience, for example, cytoarchitectonic areas are quite commonly used as the FUs of study (e.g. Sporns, 2011) for the practical reason that there are a manageable number of them (a few hundred in the cortical mantle) and on the structural and functional grounds that within these areas cytoarchitecture and receptor density distributions are fairly uniform, whereas at their boundaries these features change rapidly. In contrast, geomorphologists have given scant regard to the issue of meaningfulness of connectivity FUs. Borselli et al. (2008) present their argument on measuring connectivity in the vaguest terms of cells and components, and only in the application of the approach is a 5x5 m DTM cell introduced, but with no consideration of its meaningfulness to the objectives of the study. Cavalli et al. (2013) similarly use a DTM (2.5-m resolution) for no evident reason other than it is the highest resolution available. Although Heckmann and Schwanghart (2013) likewise use a DTM, they do briefly, but at the end of the paper, explore the implications of different resolutions and the possibility of object-based representations of topography. If geomorphology is to reap the benefits of the statistical methods and mathematical theories (e.g. graph theory, percolation theory) that connectivity science has brought to other disciplines, then any applications need to be preceded by an examination of what might constitute meaningful FUs for the particular problem to be investigated. The aim of this Commentary is to provide a foundation for such an examination.

Concepts on units of study in geomorphology

Consideration of the FUs that might be thought to comprise landscapes has a long history in geomorphology, and it was particularly active in the first half to two-thirds of the twentieth century. Wooldridge (1932) characterized topography as comprising facets of flats and slopes: “the physiographic atoms out of which the matter of regions is built” (p.32). Were Wooldridge’s characterization to be valid, then it would provide a set of FUs not dissimilar, in topographic terms, to the cytoarchitectonic areas of neuroscience: areas in which gradient remained fairly constant separated by zones of more abrupt change. A richer characterization of a landscape FU, which derives from the concept of the ‘site’ of Bourne (1931), land systems (Christian and Stewart, 1953), and land facets (Brink et al. 1966), is the land element, variously defined but always incorporating the notion of an area where the climate, parent material, topography, soil and vegetation are uniform within the limits significant for a particular application. (For a fuller discussion of this heritage see Mabbutt, 1968). Again, underpinning this characterization of landscape is the assumption that the properties of the landscape do not change at a more-or-less uniform rate, but that landscape comprises areas of relatively little change separated from each other by zones of relatively rapid change. Whilst the notion of fractals does draw this assumption into question, such a conceptualization underpins all categorical mapping of landscape such as soil and vegetation maps and is a pre-requisite for analyzing connectivity. Deriving geomorphic FUs from this conceptualization in a GIS framework promises to lead to more meaningful units from which to explore geomorphic connectivity than thoughtless adoption of DTM cells at whatever resolution happens to be available. Within any discretization of landscape used to study water and sediment connectivity is it assumed that rates and pathways of water and sediment flux remain effectively constant within FUs. Unless these FUs have some rational basis for their identification, the assumption is unlikely to be valid. Inevitably, scale issues are important. Since connectivity measures the linkages among FUs, changing the spatial scale of these FUs and the temporal scale over which fluxes are measured will likely change the observed connectivity.

The geomorphic cell

In other Earth Sciences, a variety of basic concepts of how to define FUs of study have been developed. In the following paragraph a critical reflection on their applicability for geomorphology in the context of water and sediment connectivity is presented, forming the basis for the development of the geomorphic cell concept as proposed below.

In (landscape) ecology different spatial entities ranging from patches to landscape belts or ecozones have been defined. According to the pattern-patch concept, patches are the basic units of the landscape having a definite shape and spatial configuration (e.g. Forman, 1995). A patch is further defined as being a surface area differing in appearance from its surroundings (Turner et al., 2001). Patches are connected to other patches by different types of linkages/corridors which define the connectivity of animal species between them (Beier and Noss, 1998; Bennett, 2003). By definition, patches constitute two-dimensional entities without having a vertical component. Later on, in the European school of landscape ecology, patches have been given a vertical dimension by defining so-called econs. According to Löffler (2002) an econ is the smallest, quasi-homogenous landscape unit describing vertical structural and functional relationships between the different landscape compartments/spheres (Figure 1).

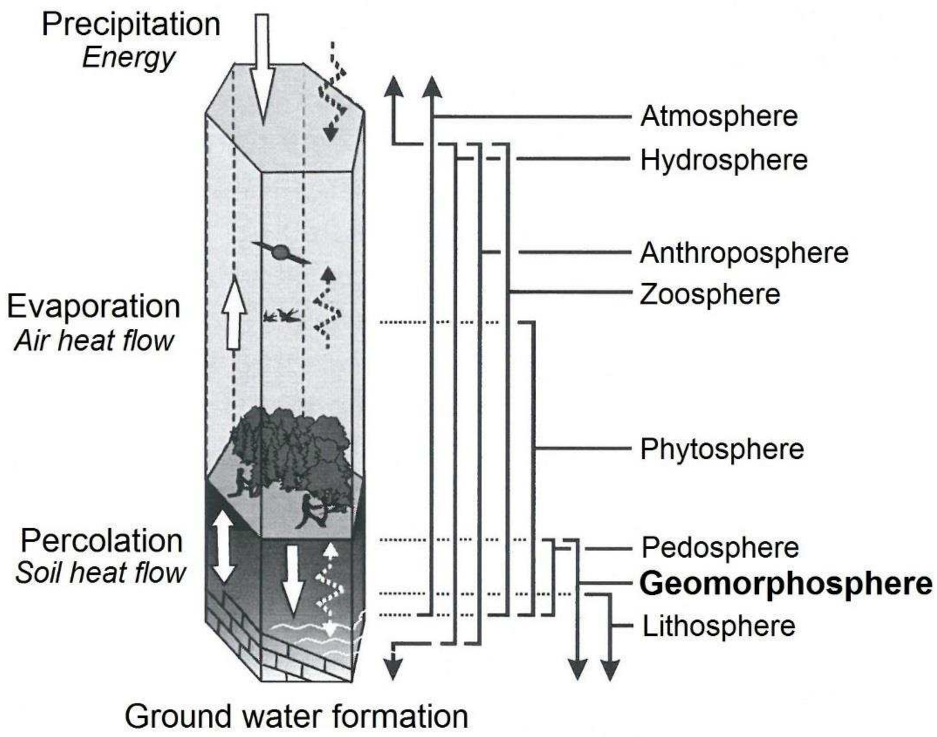

Figure 1. Landscape structure and functioning in the context of the “econ concept" using the landscape sphere model (adapted from Löffler, 2002).

Geomorphology studies the interface between the atmosphere and the lithosphere, which has also been called the geomorphosphere (Mac, 1983; see Figure 1). In the context of water and sediment connectivity we conceptualize the geomorphosphere to include all parts of the solid earth that are subject to erosion caused by water, further comprising components such as biota that influence water and sediment exchange between the geomorphosphere, the underlying bedrock (i.e. the lithosphere) and the atmosphere. For a geomorphic FU in the context of studying water and sediment connectivity, lateral linkages between neighbouring FUs as well as vertical linkages between these units and their surrounding compartments/spheres need to be taken into account. To conceptualize a geomorphic FU, a combination of both the pattern-patch and econ concepts seems to be a reasonable starting point. Both concepts, however, are lacking explanatory power when it comes to characterizing these linkages in terms of their potential to transfer water and sediment. In order to overcome these shortcomings a cellular model using analogies from cell biology is proposed.

We conceptualize the FU as being a three-dimensional body of the geomorphosphere, called the geomorphic cell, which is delimited from neighboring cells and neighboring spheres by different types of boundary. Vertically, the upper boundary of a geomorphic cell is defined by the atmosphere, while the lower boundary is generally formed by the bedrock layer of the lithosphere (in specific cases vertical boundaries may need to be adapted according to the connectivity question at hand and the geomorphic key processes involved; e.g. bedrock landslides). Following Christian and Stewart (1953), and others, we conceptualize geomorphic cells to be laterally delimited from neighbouring cells with a change in the type of land element as being defined by uniform environmental characteristics (e.g. geology, soils, topography and/or vegetation). In our conceptual model, geomorphic cells are being linked to neighbouring cells as well as to adjacent spheres by different types of linkages, here called connecteins (Figure 2). We distinguish the following three types of connectein (Table 1): Diffusive (D), channel (C), biotic (B).

Table 1. Types of connectein and their hydro-geomorphic potential of linking geomorphic cells

Connectein type	Connectivity type	Examples
Diffusive/osmotic (D)	Hydrologic: water fluxes following a concentration gradient	Vertical water evaporation/infiltration at unsealed surfaces (e.g. along soil pores), water infiltration into porous bedrock; lateral water flow in porous aquifers
Channel (C)	Hydrologic and sediment: water	Vertical water and sediment flux via soil

	and sediment fluxes following gradient	cracks or bedrock fissures; lateral water and sediment flux as concentrated throughflow in soil pipes or as overland flow in channels
Biotic (B)	Hydrologic and sediment: active water and/or sediment transport by biota	Water uptake and transpiration of plants; sediment transfer by digging animals

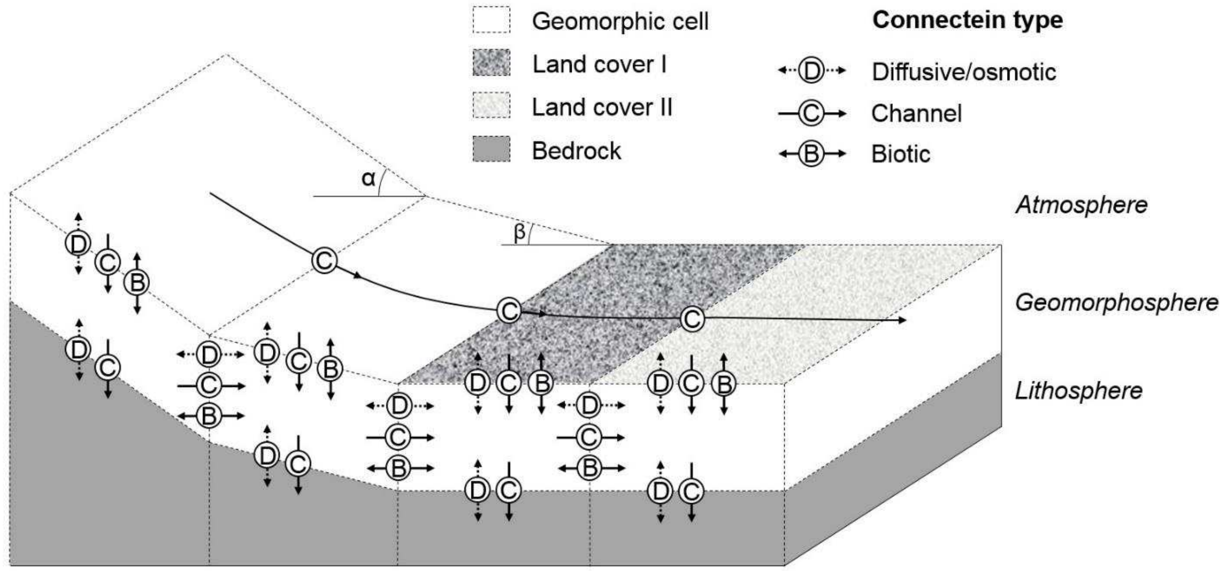

Figure 2. Schematic drawing showing a set of geomorphic cells exhibiting different in environmental characteristics (e.g. topography/slope, land cover) being laterally linked to neighbouring cells,as well as to vertically adjacent spheres (i.e. atmosphere and the bedrock layer of the lithosphere) via different types of connectein

The state of a geomorphic cell determines its functional connectivity (Figure 3). In cell biology, three states - hypotonic, isotonic, and hypertonic – determine osmotic flux. In Bioinformatics, (e.g. Müller-Linow et al., 2006), the terms active, susceptible and refractory have been used to describe the state of elements of a system. In geomorphology the current terms sink, source and steady-state can be employed. A geomorphic cell is a source if excess water and/or sediment are leaving it via one or more connecteins. A cell is in a steady state if it responds to input by delivering that water and/or sediment to adjacent cells or spheres. It is a sink if it is depleted of water and/or sediment such that some or all of the input is absorbed by the cell. The actual hydro-geomorphic state (source/steady-state/sink) of a cell is defined by the occurrence of sediment transport processes which further depends on the general availability of sediment and the sediment characteristics (i.e. sediment potential), and stream power. Vegetation may further play a critical role in influencing the system state of geomorphic cells as it is able to store and actively transport water out of the system via transpiration (i.e. biotic connecteins), while digging animals are capable of actively changing vertical and lateral connectivity relationships over time via bioturbation. Additionally, different types of human impact may alter the connectivity relationships (e.g. Poeppl et al., 2017), thereby also acting as biotic connecteins.

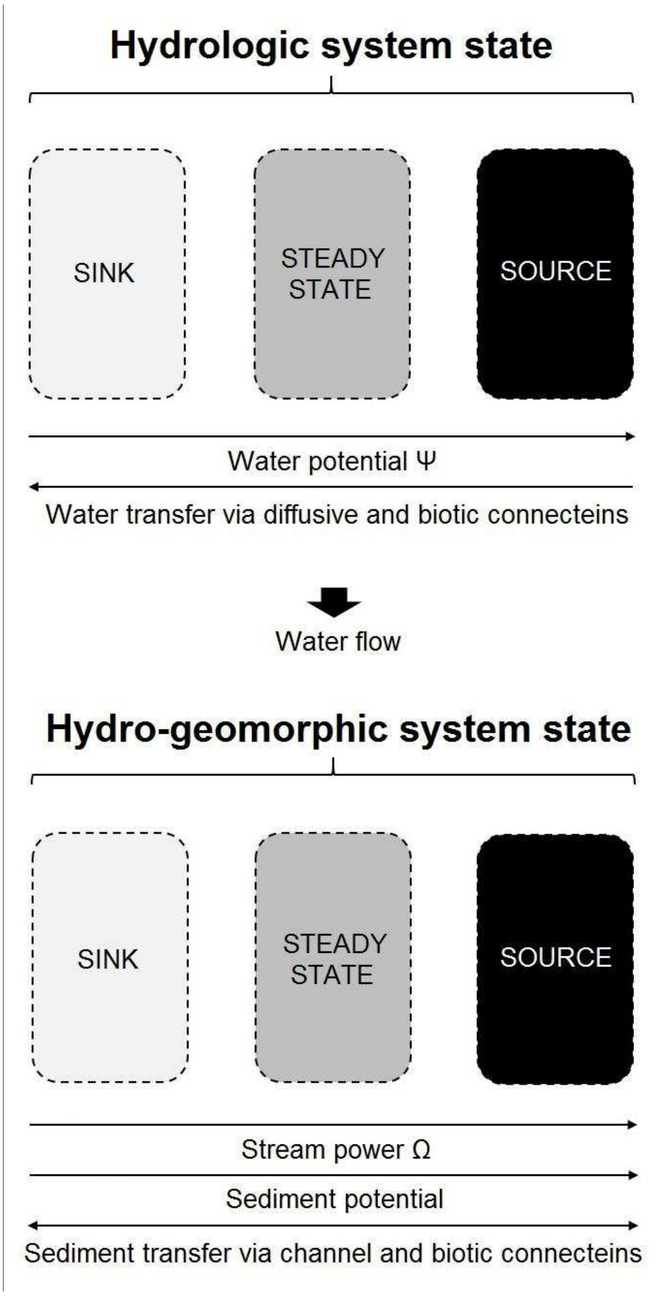

Figure 3. Schematic drawing showing different hydrologic and hydro-geomorphic system states of geomorphic cells

Implementation

We envisage that the identification of the geomorphic cells (FUs) will be undertaken within a GIS framework comprising some or all of topography, soils, lithology, vegetation and land-use layers as are appropriate to the specific investigation. Likewise, any implementation of the FU to study connectivity may use some or all of the connecteins. An example of simplest implementation might be that of Tejedor et al. (2015) in which a river delta can be considered as being composed of neighbouring cells which are in a permanent source state. These cells are connected by channel connecteins defining their potential to transfer water and sediment. In other studies, it might be appropriate to use more connecteins, and have different weightings/probabilities for them (i.e. according to the site-specific environmental conditions and/or the type of fluxes of interest), in order to express cell connectivity (see, for example, Stewart et al., 2014).

In the short term, FUs and the linkages among them define the structural connectivity of the system (Turnbull et al., 2008). If the pattern of FUs and their properties are modified by functional linkages (for example vegetation change as a result of access to water, and in the longer term topographic changes in response to sediment movement), then structural changes to connectivity will result from functional responses. Because of this interaction connectivity is an emergent property of the relationship between the two. Exploring how these interactions operate will realise the potential of connectivity to lead to insights of landscape behaviour.

Conclusion

Without prior definition of a set of meaningful entities, or fundamental units, analysis of connectivity is unlikely to yield significant geomorphic insights. Here, we have proposed the geomorphic cell as a suitable entity. We have (1) provided a means to identify these cells; (2) defined a terminology for describing cell state; and (3) identified the pathways of connections to and from cells (connecteins). The geomorphic cell is, we argue, an operationalized concept that can be employed in future connectivity research.

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