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Geomorphic coupling and sediment connectivity in an alpine catchment — Exploring sediment cascades using graph theory

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ABSTRACT

Through their relevance for sediment budgets and the sensitivity of geomorphic systems, geomorphic coupling and (sediment) connectivity represent important topics in geomorphology. Since the introduction of the systems perspective to physical geography by Chorley and Kennedy (1971), a catchment has been perceived as consisting of landscape elements (e.g. landforms, subcatchments) that are coupled by geomorphic processes through sediment transport. In this study, we present a novel application of mathematical graph theory to explore the network structure of coarse sediment pathways in a central alpine catchment. Numerical simulation models for rockfall, debris flows, and (hillslope and channel) fluvial processes are used to establish a spatially explicit graph model of sediment sources, pathways and sinks. The raster cells of a digital elevation model form the nodes of this graph, and simulated sediment trajectories represent the corresponding edges. Model results are validated by visual comparison with the field situation and aerial photos. The interaction of sediment pathways, i.e. where the deposits of a geomorphic process form the sources of another process, forms sediment cascades, represented by paths (a succession of edges) in the graph model. We show how this graph can be used to explore upslope (contributing area) and downslope (source to sink) functional connectivity by analysing its nodes, edges and paths. The analysis of the spatial distribution, composition and frequency of sediment cascades yields information on the relative importance of geomorphic processes and their interaction (however regardless of their transport capacity). In the study area, the analysis stresses the importance of mass movements and their interaction, e.g. the linkage of large rockfall source areas to debris flows that potentially enter the channel network. Moreover, it is shown that only a small percentage of the study area is coupled to the channel network which itself is longitudinally disconnected by natural and anthropogenic barriers. Besides the case study, we discuss the methodological framework and alternatives for node and edge representations of graph models in geomorphology. We conclude that graph theory provides an excellent methodological framework for the analysis of geomorphic systems, especially for the exploration of quantitative approaches towards sediment connectivity.

1. Introduction

Much of the bedrock eroded in tectonically active mountain systems is not instantaneously excavated and buried in foreland and ocean basins but stored on hillslopes and along river networks not far from its origin. The spatio-temporal unsteadiness of sediment transport between hillslopes and channels, along the channel network, and between catchments, has inspired the metaphor of a 'jerky conveyor belt' (Ferguson, 1981): Many pathways of sediment transport do not lead directly from a source to the channel network but to various storage landforms that are themselves filled and depleted. Conversely, hillslope processes may deliver sediment to channels, effectively linking upslope sediment sources to the fluvial system (e.g., Harvey, 2001). The latter does not provide spatio-temporally continuous sediment transport either, for example due to barriers (Hooke, 2003; Fryirs et al., 2007a,b).

The linkage of distinct landforms or landscape units by sediment transport is termed geomorphic coupling (e.g., Harvey, 2001). Coupling thus refers to "process domain interactions at the relatively small scale" (Faulkner, 2008, p. 91).Where sediment storage built up by a geomorphic process is depleted by another process, these processes form sediment cascades (Burt and Allison, 2010) which couple sediment sources to sinks. The degree of coupling, i.e. the combined effect of lateral (hillslope to channel) and longitudinal (from one river reach to another) linkages between system components, is termed (sediment) connectivity. Thus, connectivity refers to "the physically integrated status of a system (…) at the meso- and macro-scale" (Faulkner, 2008), a definition that also recognises connectivity as an emergent property of a geomorphic system beyond the hillslope scale (Phillips, 1999; Slaymaker, 2006).

Geomorphic coupling and connectivity have important implications for the behaviour of geomorphic systems. Above all, they have

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been recognised as a major factor of sediment budgets and thus a major research problem in geomorphology (Caine and Swanson, 1989; Harvey, 2001, 2002; Hooke, 2003; Brierley et al., 2006; Fryirs et al., 2007a,b; Borselli et al., 2008; Faulkner, 2008; Harvey, 2012). Researchers have presented sediment budgets on various spatial and temporal scales with respect to system compartments acting as sources or sinks, and to sediment fluxes between these compartments (e.g., Dietrich and Dunne, 1978; Trimble, 1983, 2009; Keesstra et al., 2009). In such a framework, it is essentially sediment (dis)connectivity that leads to a discrepancy between erosion within the catchment and sediment yield at its outlet, which varies with spatial scale (the 'sediment delivery problem', Walling, 1983; de Vente et al., 2007). Moreover, a thick sediment cover will protect channel beds from erosion with long-term implications for landscape evolution (Pratt-Sitaula et al., 2004), geomorphic extreme events are largely fueled by remobilisation of sediment accumulated in hillslope storage (Korup, 2012), and short-term variability of sediment storage in channels strongly influences river sediment discharge and habitats (Montgomery and Buffington, 1997). Through the modification of sediment conveyance through a catchment, connectivity is also an important factor for the up- or downstream propagation of changes and the reaction of a system to disturbance (Brunsden and Thornes, 1979; Brunsden, 2001; Harvey, 2001, 2007). The response of catchments with different internal configuration (and thus different connectivity) to the same climatic input may diverge extremely (Wainwright, 2006), thus aggravating the interpretation of sedimentary archives (Brierley et al., 2006). Finally, connectivity is subject to considerable spatiotemporal variability, governed by physical and biological thresholds that induce nonlinear response to even small changes on all scales (Cammeraat, 2002). Brierley et al. (2006) emphasize the potential of hydrological connectivity (consequently of sediment connectivity as well) for the understanding of complex systems, and even for integrated catchment management.

We argue that despite its widely recognised importance, connectivity has mainly been treated qualitatively and that there is a need for more quantitative approaches. While landscape ecologists have already developed a large number of different indices for the quantification of landscape connectivity (e.g., Calabrese and Fagan, 2004), and hydrologists have increasingly started to look in the same direction (e.g., Bracken and Croke, 2007; Ali and Roy, 2009, both also with reference to geomorphology), almost all geomorphological studies dealing with geomorphic coupling or sediment connectivity are based on the qualitative interpretation of geomorphological maps. Caine and Swanson (1989) describe differences in hillslope-channel coupling to explain differences in the sediment yield of two small mountain catchments. Harvey (2001) shows geomorphological maps with zones of hillslope-channel coupling and highlights the importance of debris flows in sediment delivery to channels; spatio-temporal scale issues of geomorphic coupling in fluvial systems are discussed, e.g., by Harvey (2002). A methodological framework for an appraisal of coarse sediment connectivity is introduced by Hooke (2003) who uses five categories (*fully*, *partially or potentially connected*, *un- and disconnected*) of river reaches based on the interpretation of morphological and granulometric field evidence. Korup (2005) establishes a nominal classification scheme for the coupling interface between landslides and the fluvial system (*area*, *linear*, *point*, *indirect*, *nil*). Brierley et al. (2006) define forms of landscape (dis-)connectivity with respect to the transfer of matter on various spatial scales, and discuss the implications for catchment response to changes and even for potential management applications. Based on these considerations, Fryirs et al. (2007a,b) analyse two catchments with respect to sediment cascades, impediments to sediment conveyance (*buffers*, *barriers and blankets*) and sediment budgets. Reid et al. (2007) include hydrological connectivity in modeling the delivery of coarse sediments generated by landslides to the channel system. Faulkner (2008) discusses the role of connectivity changes for badland evolution. From denudation measurements in a steep alpine catchment and multitemporal mapping of areas of hillslope-channel coupling on aerial photos, Schlunegger et al. (2009) conclude that denudation rates and sediment yield are higher, and the (re-)formation of a vegetation cover is impeded on coupled slopes. Quantitative approaches towards sediment connectivity are widely absent with few exceptions. Borselli et al. (2008), for example, derive a connectivity index (IC index) based on a raster DEM which combines upslope contributing area and gradient-weighted downslope flowpath length. Vigiak et al. (2012) report that the inclusion of this 'flux connectivity index' significantly improves modeled estimates of catchment suspended sediment yield. Another issue is a lack of theory or at least insufficient conceptionalisation with respect to inferring connectivity as a system property from localised observations of (de-)coupling.

In this study, we propose a network analysis approach towards quantifying connectivity using graph theory. While we will not devise a connectivity index (which is subject to ongoing research), we show how a spatially explicit graph model is established to structure and store data on sediment pathways. Graph theoretical methods are used to delineate the sediment contributing area of any site within a high-mountain catchment, and to analyse sediment cascades that result from the spatial interaction of sediment pathways and the corresponding process domains (Becht et al., 2005; Wichmann et al., 2009). Our study aims at analysing the spatial distribution and composition of such cascades. In aggregating the information of many single, site-specific cascades, we expect details to be lost, but major structures to emerge. Finally, a conceptual model of a (sub-)catchment can be generated through a (semi-)automated approach. In addition, the aim of this study is to substantiate a spatially explicit network analysis approach in geomorphic system analysis and to highlight the potentials of graph theory as a methodological framework.

2. Theoretical framework

2.1. Graph theory

Network analysis is carried out in many research areas such as social networks, transportation systems, communication networks, statistical mechanics, and population and landscape ecology. Networks refer to objects composed of elements and interactions or connections between these elements. Ecological networks, for example, consist of habitat patches the linkage of which is determined by environmental conditions and species mobility (e.g., Bunn et al., 2000; Urban and Keitt, 2001). All of these applications rely on a coherent formal basis to represent, measure and model the relational structure of networks (Barabási, 2009; Butts, 2009; Newman, 2010). The mathematical model of networks is the graph, and the study of graphs is termed graph theory. The tools provided by graph theory have helped to tackle a number of generic problems of complex systems, e.g. describing and assessing network structure, understanding exchange of matter, energy and information in networks, modelling propagation of system changes through networks, modelling the effects of changes in network structure and finding universality in network topology (Butts, 2009).

A graph is an abstract structure that includes objects (nodes or vertices) that are connected by links (edges). Formally, a graph is defined as $G=(N,E)$, consisting of the two disjoint sets nodes N and edges E. Graphs can be directed (digraph) if a direction can be attributed to the edges, otherwise the graph is undirected. The basic representation of a graph is its adjacency matrix A. A is a square matrix with as many rows and columns as there are nodes in G. Its elements a_{ij} refer to the number of edges between the nodes i and j. In undirected graphs, A is symmetric to the main diagonal. A graph is termed weighted if each edge is associated with usually real number weights (Newman, 2010); these weights can represent, for example, distance, friction, resistance, or flux rates of matter or energy.