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Preface: Complexity (and simplicity) in landscapes

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The 2007 Binghamton Geomorphology Symposium, entitled Complexity in Geomorphology, focuses on the nature of complexity in geomorphic systems. 'Complexity' mean various things in different contexts, but in the sciences in recent years 'complex systems' or 'complexity theory' have come to refer to a collection of related perspectives and techniques arising initially from research in nonlinear dynamics. Papers in this special issue exemplify how these approaches are helping advance an understanding of geomorphic processes and patterns. The topic of complexity has become important to geomorphologists in several disciplines (geology, geography, geophysics, engineering, and others). Many of the theories of complexity, the methods of understanding its nature, and insights concerning complex geomorphic systems, however, have not leaked from one discipline to another, nor from one topical branch of geomorphology to another. The need for a forum dedicated to complexity in geomorphology suggested that the time was right to bring together an interdisciplinary and international group of papers on the subject, and this volume is the result.

Some of the most important complex-systems perspectives imply that in landscapes (as well as in other physical and biological systems), cause and effect may not be related in the direct ways that we might assume; forcing may not produce response in a straightforward way. For example, chaos theory showed that even dauntingly complicated, apparently random (stochastic) behaviors may stem from simple underlying interactions. Nonlinear interactions often involve multiple feedbacks that lead to surprising and rich, perpetually changing behaviors—behaviors that create themselves, in the sense that 'events' do not correspond to changes in the forcing. And simple, local nonlinear interactions can provide the basis for the self-organization of global patterns that do not correspond to any forcing template.

The related emergent-phenomena perspective points out that analyzing the building blocks of a system—the small-scale processes within a landscape—may not be sufficient to understand the way the larger-scale system works. The collective behaviors of the many small-scale degrees of freedom synthesize into effectively new interactions that produce large-scale structures and behaviors, the way that molecular dynamics in a fluid give rise to what we characterize as macroscopic variables, which can then interact to form water waves, for example.

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And these emergent structures can then strongly influence the smaller scale processes, the way that waves affect molecular motions or an eolian dune determines the patterns of wind-blown sand fluxes and avalanching. Thus, when nonlinear feedbacks lead to the self-organization of large-scale patterns and behaviors, causality extends in both directions through the scales, and the most 'fundamental' scale on which to base an analysis may not be the smallest. The extent to which these scale-related phenomena imply that a hierarchy of scales for models and understanding is required in geomorphology is still under vigorous debate.

The concept and mathematics of fractals arose arm-in-arm with nonlinear dynamics, and the 'strange attractors' that can characterize chaotic systems. The self-similarity or self-affinity of a landscape (including the extension of multifractality), detected and quantified by power-law scalings, suggest that the same dynamics—the same cause in this sense—produce similar effects across a wide range of scales (Mandelbrot, 1982). Power-law scaling can also arise from self-organized-critical behavior, in which events of any scale can occur at any time under constant forcing, with probabilities that vary in a self-similar way across the scales.

Turbulence provides the archetypical example of several of these concepts. Even in the simple physical system of fluid flowing in an open channel, forced steadily by gravity, nonlinear feedbacks feast on velocity shear to produce emergent structures—eddies—that then interact with each other to produce an intricate array of structures at different scales. The interaction between two eddies of a similar size dictates the flow dynamics at the next smaller scale, creating new shear zones and, thus, smaller eddies. A myriad of such interactions give rise to a scale-independent trend (power-law scaling) in the time-averaged distribution of turbulent energy across scales, and to self-organized heterogeneity in the temporal and spatial structure of the flow, which manifests itself as intermittent bursts of activity (characterized by multifractality).

1. The turbulence analogy and power-law scaling

The turbulence analogy can spur insights about landscape processes when applied directly (Murray, in press-b), as the papers by Haff and Pelletier do in this volume. After analyzing a simple set of equations that shed light on what kind of interactions are sufficient to produce perpetually dynamic evolution in fluvially carved landscapes, Pelletier's article explicitly relates the behavior of this model to ever-dynamic case of turbulence. Haff focuses more on the spatial structures of landscapes, discussing several illuminating points including: 1) how under some circumstances longitudinal river profiles equate formally to the law of the wall in turbulent flow; 2) how a Reynolds number can be defined for landscapes, interpreted as a ratio of advective to diffusive transport, or as the range of scales between the largest valleys and the smallest hollows, just as it can be interpreted as the ratio of the largest eddies (characteristic system length scale) to the viscous-dissipation length scale in turbulent flow; and 3) how the evolution of the scale-independent nested valley structure corresponds to the cascade from large to small scales in turbulence.

The turbulence analogy is also applied less explicitly in several papers that examine landscape scaling, such as the papers by Pelletier, Turcotte, D'Alpaos et al., Gangodagamage et al., Baas, and Coulthard et al. Gangodagamage et al. show that the width of valleys, at elevations not far above the valley bottom, exhibit a multifractal structure. The papers by Pelletier and Turcotte reference the fractal aspects of topography and drainage networks before proposing or reviewing, respectively, simple models that lend insight into how these properties could come about. D'Alpaos et al. use the scaling properties of a tidal-channel network as a test of an elegant numerical model of network development.

Power-law scaling in geomorphology is extremely common through space and time (e.g. Rodriguez-Iturbe and Rinaldo, 1997). Several theories postulate mechanisms that would produce such scaling, but it has been difficult to determine when these various mechanisms are or are not actually at work. One of the most commonly proposed mechanisms is self-organized criticality, or SOC (Bak et al., 1987). SOC postulates that temporal power-laws ($1/f$ noise) and spatial power-laws (fractals) result from the local exceedance of stability thresholds, and the subsequent effects on neighboring areas that may then also exceed the threshold. Researchers have suggested SOC-like dynamics in many geomorphic phenomena (Fonstad and Marcus, 2003), including landslides, avalanches, river-bank instability, network generation, river meandering and braiding, and seismically-active landforms. In a paper in this volume, Hooke suggests that in river meanders, autogenic dynamics produce a self-organized form, and that the fluctuations of these forms would be expected given an SOC-like process. The importance of these dynamics is not simple to tease out of existing data, and their role in meandering is not well-understood.

The ubiquity of power-law scaling makes it difficult to prove or disprove SOC theory directly. Current work, such as that in this volume by Coulthard et al. and