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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

Hooke, suggests that searching for the actual local-scale threshold mechanisms that would transmit a cascade effect to neighboring areas may be an important method of clarifying the importance of SOC in geomorphology. Coulthard's highly detailed CAESAR model allows a first step in this direction, and shows how various climate events are constrained by river basins and transformed into self-organized signals of water, sediment, and geomorphological dynamics through time. More advanced methods of testing SOC, such as renormalization group procedures used for testing SOC in some branches of physics, have not yet been imported into the landscape sciences. Other theories of power-law scaling, such as highly-optimized tolerance (Carlson and Doyle, 1999), have hitherto not been widely explored.

2. Simple models: emergent and self-organized behaviors

Power-law scaling, so commonly observed on the surface of Earth, characterizes fascinating and useful, stochastic aspects of landscapes. This stochastic behavior or outcome, however, does not preclude searches for relatively simple, deterministic interactions that could explain the complicated observations (Murray, in press-b). Such endeavors can be seen as of the essence of the complex-systems approach. Exploring whether simple, nonlinear interactions could produce the complex special and temporal structures observed in natural landscapes often calls for a numerical model with abstracted representations of the processes hypothesized to be important. As a complement to 'simulation models' designed to be as quantitatively accurate as possible, such highly simplified 'exploratory models' facilitate the clearest potential insights about the interactions and modes of self-organization that might be operating in poorly understood natural systems (Murray, 2003, in press-c). Such models often employ a 'top-down' or 'hierarchical' strategy (Murray, 2003; Paola, 2000; Werner, 2003); rather than explicitly representing the processes in a landscape at scales as small as is practical, they start directly with the larger-scale variables and interactions that emerge from the collective behavior at much smaller scales—variables and interactions that most directly produce the larger-scale phenomena.

Several papers in this volume describe models based on these approaches, and the complex behaviors they produce. The article by Jermolack and Paola presents a model of river-avulsion dynamics in which avulsion itself is treated as simply as possible, to examine the behaviors that arise spontaneously in a spatially extended domain. They consider avulsions as an emergent result of smaller- and faster-scale processes, and treat them as just a threshold involving local relief between channels and floodplain. The complex spatial and temporal patterns that then emerge suggest that the self-organized, or 'autogenic' events, arising from dynamics internal to the model system, could account for shifts in river behavior and the resulting stratigraphy that might otherwise be attributed to changes in external forcing (tectonic or climatic shifts) when observed in nature.

Coulthard's CAESAR model of fluvial nonlinearity and river basin evolution combines several layers of geomorphology and hydrology to show how signals transmitted through a geomorphic system are constrained and spread out, producing self-organized time-varying behavior. As in the Jermolack and Paola avulsion model, this self-organization obscures the causal relationship between forcing changes, such as climate change, and system responses.

Reduced complexity models are also used in the papers by Baas and by Zeng et al. to describe how self-organized macroscale forms (such as various classes of dunes in Baas's study or diverse treeline ecotone patters in Zeng et al.'s paper) can be understood by considering the iterative dynamics of local interactions under different external forcing regimes. Baas's use of several classes of reduced-complexity model show how aeolian landforms, subject to a range of external forcing conditions, self-organize into recognizable forms, and how these forms are produced within a scale hierarchy of processes.

In a similar spirit, Howard employs simplified model interactions to explore the modes of landscape evolution that could have produced Martian landscapes, where precipitation/evaporation, fluvial, lacustrine, and cratering processes have likely all interacted. Several potential insights result, including the conclusion that the lack of well integrated drainage networks may not reflect a weak fluvial influence, as our terrestrially based intuition suggests.

Coco and Murray review models of nearshore pattern formation, ranging in scale from beach cusps (10^1 m) to coastline shapes and patterns of change (10^5 m). Across these scales and the different environments involved, in recent years simple models of morphodynamic feedbacks and subsequent self-organization provide plausible explanations for phenomena that were previously ascribed to (often hypothetical) external forcing templates. McNamara and Werner's paper includes a reduced-complexity cellular and agent-based model of human-geomorphic relationships that reproduces the history of economic and infrastructure development in New Orleans, offering potential insights into the interactions behind the patterns of development.

Turcotte's article reviews how abstracted analytical and numerical models provide clues about the basic aspects of natural processes that could explain the emergence of fractal topography and river networks. The papers by D'Alpaos et al. and Pelletier, both mentioned in the previous section in the context of power-law scaling, also fit in the present context, offering models that can help us understand fundamental aspect of landscape evolution.

3. Other sources of complexity: catastrophes, contingency, biology and intentionality

Howard's paper, along with providing an excellent example of the use of exploratory modeling to produce clear insights that could be relevant in natural systems, points out a sense of 'complexity' that is somewhat different than the notion of complicated behavior arising from simple interactions under a constant forcing. In his Martian-landscape model, simple treatments of fluvial processes alone would produce complex landscapes (as he and others have shown). The repeated disruption of the fluvial landscape evolution process by impact cratering, however, prevents a typical landscape (by Earth standards) from developing. Instead, the ongoing alternation of crater formation and fluvial re-sculpting leads to a different, yet unquestionably complex, landscape. From the fluvial-process viewpoint, the episodic crater formation could be considered as stochastically changing forcing/boundary conditions. On the other hand, viewed more holistically, the iterative sequence of process alternations constitutes a distinct mode of pattern formation and complexity.

The paper by Phillips calls attention to another sense of complexity that involves the combined influences of generally applicable processes and place-specific contingencies. He points out that in most instances of pattern formation or landscape evolution, peculiarities associated with the location—such as fluvial incision into resistant substrates in his case study—will interact with more universal influences to produce a unique landscape in each case.

This point highlights a significant difference in perspectives and goals among different geomorphologists. Phillips' paper reflects an inclination to understand the unique origins of particular landscapes. In this perspective the specific historic sequence of processes, forcing and boundary conditions that brought that landscape into existence are just as important as the more universally applicable influences tending to shape the landscape presently. It is in this perspective that landscape sensitivity to initial conditions (one of the properties of chaotic systems) becomes significant, further reinforcing the conclusion that no two landscapes will be the same. Other geomorphologists tend to focus more on general landscape-forming processes—to focus more on what is common among similar landscapes than on the differences between them. From this perspective, pre-existing particularities or palimpsests in specific locations tend to be viewed as initial or boundary conditions, or as the perturbations that kick off generally applicable instabilities (nonlinear feedbacks) and modes of pattern formation. With this mindset, the particular source of perturbations are not a key element of the story of how some landscape type tends to form; there are always perturbations of some sort always occur in nature, and the fewer the details included in a model (conceptual, analytical or numerical) the better. Which of these end-member viewpoints each of us leans toward is a matter of taste and sociology, rather than a cause for value judgments, and they are complimentary approaches in any case.

Geomorphologists are beginning to devote considerable attention to two-way couplings between biological and physical processes, which can lead to intriguing feedbacks and emergent behaviors, and can be essential to understanding some landscapes (Baas, 2002; Fonstad, 2006; Murray, in press-a), as the papers by Zeng et al. and Baas exemplify. Biological processes interacting with geomorphological processes can set into motion feedbacks that may eventually alter the clustering and organization of both processes sets. Zeng et al.'s paper shows how even subtle landforms can influence the spatial grouping of alpine treeline vegetation. As these treelines then influence the alpine soils and hydrology, the periglacial landforms are themselves spatially altered.

The papers from Haff and McNamara and Werner illuminate another distinct source of complexity that is rapidly gaining influence in Earth-surface processes: humans. Human–landscape couplings are becoming almost as ubiquitous as those involving plants and (other) animals, but carry with them another layer of nonlinear interactions that are especially challenging to model—those that occur within human minds and societies. Human intentionality and societal evolution drive the exponential technological advance we are witnessing, and Haff's paper is beginning to incorporate the effects of technology into a complex-systems analysis of anthrogeomorphology. McNamara and Werner's paper lays out a vision for how to model coupled human–landscape evolution, and provides an example in which floods interact with human economics and infrastructure in New Orleans to produce long-term dynamics that would not occur without the coupling. The inclusion of rules representing human intentionality, combined with the identification of the time scales of effective human–landscape coupling, constitutes a new approach in geomorphology that could be incorporated into other studies.

4. Closing thoughts

We believe that the group of papers in this volume provides a useful overview of complexity-related research in geomorphology. A growing body of literature is identifying the need to employ complex-systems perspectives and methods to understand and predict landscape evolution and change (e.g. Malanson, 1999; Werner 1999; Werner 2003). As the complex nature of many geomorphic phenomena becomes clearer, the need for researchers skilled in the analysis of complexity will increase. We hope that this volume will spur discussion and collaboration, and will aid in the training of the next generation of geomorphologists.

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References

Baas, A.C.W., 2002. Chaos, fractals and self-organization in coastal geomorphology: simulating dune landscapes in vegetated environments. Geomorphology 48 (1), 309–328.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of 1/*f* noise. Physical Review Letters 59 (4), 381–384.

Carlson, J., Doyle, J., 1999. Highly optimized tolerance: a mechanism for power laws in designed systems. Physical Review E 60, 1412–1427.

Fonstad, M., 2006. Cellular automata as analysis and synthesis engines at the geomorphology–ecology interface. Geomorphology 77, 217–234.

Fonstad, M.A., Marcus, W.A., 2003. Self-organized criticality in riverbank systems. Annals of the Association of American Geographers 93 (2), 281–296.

Malanson, G.P., 1999. Considering complexity. Annals of the Association of American Geographers 89 (4), 746–753.

Mandelbrot, B., 1982. The Fractal Geometry of Nature. Freeman, San Francisco, CA.

Murray, A.B., 2003. Contrasting the goals, strategies, and predictions associated with simplified numerical models and detailed simulations. In: Iverson, R.M., Wilcock, P.R. (Eds.), Prediction in Geomorphology. AGU Geophysical Monographs, pp. 151–165.

Murray, A.B., in press-a. Biomorphodynamics in river, coastal and estuarine settings. In: 5th International Symposium on River, Coastal and Estuarine Morphodynamics, Utrecht.

Murray, A.B., in press-b. Two paradigms in landscape dynamics: Self-similar processes and emergence. In: A.A. Tsonis and J.B. Elsner (Editors), 20 Years of Nonlinear Dynamics in Geophysics. Springer.

Murray, A.B., in press-c. Reducing model complexity for explanation and prediction. Geomorphology.

Paola, C., 2000. Quantitative models of sedimentary basin filling. Sedimentology, 47 (Suppl. 1), 121–178.

Rodriguez-Iturbe, I., Rinaldo, A., 1997. Fractal River Basins: Chance and Self-organization. Cambridge University Press, Cambridge, NY.

Werner, B.T., 1999. Complexity in natural landform patterns. Science, 284, 102–104.

Werner, B.T., 2003. Modeling landforms as self-organized, hierarchical dynamic systems. In: Iverson, R.M., Wilcock, P. (Eds.), Prediction in Geomorphology. AGU Geophysical Monographs, pp. 131–150.