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Sources of nonlinearity and complexity in geomorphic systems

Jonathan D. Phillips

Tobacco Road Research Team, Department of Geography, University of Kentucky, Lexington, KY 40506, USA

Abstract: Nonlinearity is common in geomorphology, though not present or relevant in every geomorphic problem. It is often ignored, sometimes to the detriment of understanding surface processes and landforms. Nonlinearity opens up possibilities for complex behavior that are not possible in linear systems, though not all nonlinear systems are complex. Complex nonlinear dynamics have been documented in a number of geomorphic systems, thus nonlinear complexity is a characteristic of real-world landscapes, not just models. In at least some cases complex nonlinear dynamics can be directly linked to specific geomorphic processes and controls. Nonlinear complexities pose obstacles for some aspects of prediction in geomorphology, but provide opportunities and tools to enhance predictability in other respects. Methods and theories based on or grounded in complex nonlinear dynamics are useful to geomorphologists. These nonlinear frameworks can explain some phenomena not otherwise explained, provide better or more appropriate analytical tools, improve the interpretation of historical evidence and usefully inform modeling, experimental design, landscape management and environmental policy. It is also clear that no nonlinear formalism (and, as of yet, no other formalism) provides a universal meta-explanation for geomorphology. The sources of nonlinearity in geomorphic systems largely represent well-known geomorphic processes, controls and relationships that can be readily observed. A typology is presented, including thresholds, storage effects, saturation and depletion, self-reinforcing feedback, self-limiting processes, competitive feedbacks, multiple modes of adjustment, self-organization and hysteresis.

Key words: chaos; complexity; dynamical instability; geomorphology; nonlinearity; self-organization.

I Introduction

Nonlinear dynamics and complexity have been widely discussed in the scientific literature, including geography, geology and geomorphology. A wide variety of terms, phenomena and scientific subcultures have emerged, including (to name a few) nonlinear science, nonlinear dynamical systems, complexity science, complexity theory,

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self-organization, chaos and fractals. Geomorphologists are aware of these notions and threads of inquiry. However, there are several inaccurate or outdated general perceptions in the geomorphological community about complex nonlinear dynamics. One is that this type of complexity, while readily generated by certain types of equation systems, simulation models and controlled experiments, has not been widely or convincingly demonstrated in real-world earth surface processes and landforms. Another perception is that some types of nonlinear complexities, such as deterministic chaos, imply an inability to predict or to even advance our comprehension of nature. Some earth scientists have also been put off by claims on behalf of some strains of nonlinear theory (for example self-organized criticality) that they represent meta-explanations for nature.

The presence of nonlinear complexities in geomorphic (or other systems) is not necessarily pathological, and may enhance some modes of understanding and predictability even as it inhibits other modes. Most scientists exploring nonlinear dynamics and developing and applying related theories do not make claims of meta-explanation. Complex nonlinear dynamics is not an artifact of models, equations and simplified experiments, but has been observed and documented in many geomorphic phenomena. Further, nonlinear dynamics are not rare and isolated in geomorphic systems. The identification of nonlinear complexities in landforms and surface processes is, furthermore, not trivial. It has profound implications (in terms of opportunities as well as constraints) for prediction, explanation and application in geomorphology.

If the study of nonlinear complexities is to result in significant progress in geomorphology, then those complex phenomena must be directly linked to relevant, observable processes, histories, patterns, relationships or structures in the landscape. This may occur by adapting and applying concepts and methods from nonlinear science developed in other fields to geomorphology. It is more effective, however, to confront nonlinearity in geomorphology based on earth science concepts. In other words, inquiry should be problematized from a geomorphological perspective rather than an abstract nonlinear dynamics perspective.

The goal of this paper is twofold. First, arguments will be presented to support the assertion above, that complex nonlinear dynamics are common and relevant in real (as opposed to model) earth surface systems. This will largely be accomplished in the context of a discussion and illustration of why it is important to study nonlinearity. Secondly, a typology of the sources of nonlinearity in geomorphic systems will be developed, identifying archetypal mechanisms and functional relationships that lead to nonlinear behavior, and citing concrete examples.

Reviewing basic concepts of nonlinear dynamics is not a goal of this paper. There are numerous texts discussing these concepts from mathematical and systems theory perspectives, and several which address them in an earth science context (Scheidegger, 1990; Turcotte, 1997; Phillips, 1999). In addition, there is a general introductory book on chaos theory written by a geomorphologist (Williams, 1997). Some short and superficial definitions are given in Table 1.

This synthesis is biased toward work that has a significant field component. This is not to deny the importance and influence of modeling and laboratory studies, which have generally, at least to this point, been more common and significant in the study of nonlinear dynamics than in any other aspect of geomorphology. However, given the nature of the discipline, where 'field relations are the final court of appeal' (Bretz, 1962)

Table 1 Definitions of some common types of complex nonlinear dynamics

Chaos (deterministic chaos)	Sensitivity to initial conditions and small perturbations, whereby initial differences or effects of minor perturbations tend to persist and grow over time
Dynamical instability	The effects of small perturbations tend to persist and grow over finite time, and are disproportionately large and long-lived compared with the initial perturbation. In many situations dynamical instability and chaos are interchangable
Fractals	Patterns, forms and structures are fractal when their Hausdorff dimension is greater than their Euclidian dimension. Surfaces, for instance, are fractal if their geometry is too complex to be described with a differentiable function, and when $2 < H < 3$, where H is the Hausdorff dimension and 2 and 3 are the Euclidean dimensions of a planar surface and of a volume. Fractals are also self-similiar or self-affine, such that their basic structure is scale-invariant. Fractal statistics are used as a morphometric descriptor of many forms and patterns produced by complex nonlinear dynamics, and are mathematically linked to chaos and other forms of nonlinear complexity
Multiple equilibria	There are two or more possible system states or modes of adjustment (defined either at a specific point in time, or as a developmental trajectory) to a given set of inputs and boundary conditions
Strange attractors	In a state space defined by all the variables or components of a system, the region of the space to which all evolutionary trajectories are drawn is an attractor or basin of attraction. Attractors may be simple and compact or broad and complex. Where the attractor is complex and characterized by nonrepeating trajectories, it is referred to as a strange or chaotic attractor
Self-organization	Formation and maintenance of patterns or structures attributable to the internal dynamics of a geomorphic system, independently of external controls or inputs. There are many semantic as well as geomorphic varieties of self-organization, not all linked to complex nonlinear dynamics. There are a number of self-organization concepts involving various forms of autocatalysis and self-regulation that may be, but are not necessarily, linked to complex nonlinear dynamics. Those variants of self-organization explicitly linked to nonlinear formalisms include self-organization as:
	Trend toward maximum entropy: entropy maximization in many cases is directly associated with dynamical instability and chaos, and entropy can be used as an indicator and measure of 'chaoticity'
	System maintenance by energy dissipation: systems maintain their structure by dissipating energy far from thermodynamic equilibrium
	Divergent self-organization: occurs because of divergent evolution associated with instability and chaos, but such that the limits of unstable divergence result in broader-scale patterns or regularities
	Self-organized criticality: a tendency to evolve toward critical or threshold states
	Systematic rank-size distributions: these distributions are often characterized by self-similar or self-affine fractals, and have been linked to self-organized criticality, fractal distributions of forcing functions, self-reinforcing feedbacks, nonlinear cascades of mass and energy through scale hierarchies and nonlinear storage effects

and the field-oriented culture of geomorphology, the typical geomorphologist, while recognizing the critical roles of theory, modeling and experimentation, ultimately finds work with a field component most convincing. Also, the goal of this paper to link nonlinearity to earth surface observables necessarily dictates an emphasis on work with an empirical component. This paper is also not intended to be a comprehensive catalog of nonlinearity in geomorphology. The review is selective in the sense of an attempt to cite examples that represent particularly clear, intuitively appealing or uncluttered examples of particular types of nonlinearity.

1 What is nonlinearity?

A system is nonlinear if the outputs are not proportional to the inputs across the entire range of the inputs. In applying nonlinearity to earth surface systems, the terms 'input' and 'output' may need to be more broadly and flexibly defined than their mathematical or systems theory meanings. In terms such as 'nonlinear dynamics' and 'nonlinear science', nonlinearity has come to be associated with various aspects of nonlinear behavior such as chaos, fractals and complex self-organization (see Table 1). While this conflation of nonlinearity and complexity may be unfortunate and at least partly inaccurate, the connotations are entrenched.

Nonlinearity in earth surface systems indeed opens up a variety of possibilities for complex behavior that are not possible in linear systems. However, we must recognize that nonlinear systems may be simple and predictable. We also recognize that complexity has causal roots other than nonlinearity. In this paper I am concerned with that subset of nonlinear behavior that leads to (the possibility of) complex behavior, poses potential problems for predictability or dictates the application of an explicitly nonlinear approach or perspective (Figure 1). I am concerned with that subset of

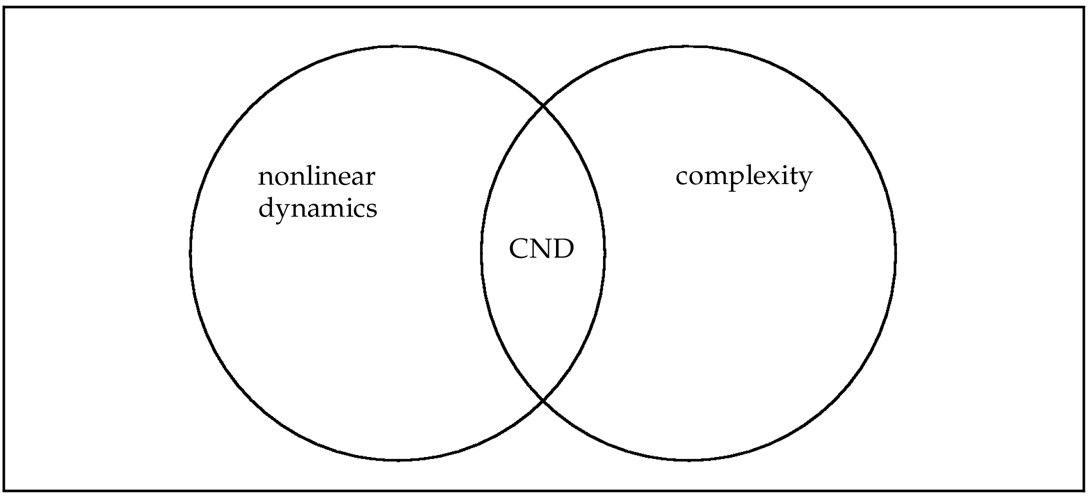

Figure 1 Not all nonlinear dynamics are complex; not all complexity is nonlinear or intrinsic to system behavior. Complex Nonlinear Dynamics (CND) represents the complexity that does arise from intrinsic nonlinearities

complexity, unpredictability and uncertainty that arises from nonlinearities. This does not imply that other sources of complexity and unpredictability are not interesting and important!

II Why is nonlinearity important?

1 Interpretation of historical evidence

Complex nonlinear dynamics may complicate efforts to interpret historical evidence such as stratigraphy, paleosols and paleoecological data. Because of dynamical instabilities and chaos, small perturbations or short-lived disturbances rather than larger environmental change may be responsible for changes or switches. Because of multiple equilibria, there may not be a one-to-one correspondence between system states and environmental controls.

For example, the nonlinear dynamical systems models of Thornes (1985) and Kirkby (1995) show that in semi-arid systems the equilibrium relationship between vegetation and soil erosion is unstable. This implies that, if disturbed, the system will 'tip' to either a maximum vegetation/no erosion or maximum erosion/no vegetation state. Subsequent work in semi-arid systems has validated this, showing the tendency of disturbed semi-arid landscapes and ecosystems to diverge into well-vegetated and noneroded versus unvegetated and highly eroded patches (Abrahams *et al.*, 1995; Puigdefabregas and Sanchez, 1996). Thus, stratigraphic, pedological or ecological evidence of a vegetation change or the onset of an erosion episode may not imply a major change in climate, land use or other forcings, but merely the 'tipping' of an unstable system in response to a small, short-term perturbation such as fire, a severe storm or the grazing of a bison herd.

Harper (1998) discusses chaos in the context of methods for testing the presence and significance of thickening or thinning sequences in strata. Dearing and Zolitschka (1999) have explicitly addressed the implications of nonlinear complexities in interpreting lake sediment archives, and demonstrate how complex internal dynamics rather than external forcings account for some observations in the sediment record of a German lake. In coastal onlap stratigraphy, Gaffin and Maasch (1991) show that multiple equilibria associated with nonlinear feedbacks can result in large onlap shifts associated not with accordingly large sea-level change, but rather arising from small perturbations. Steep-faced glaciodeltaic progradational successions have often been studied to reconstruct the behavior of the glacial feeder system or changes in the sediment sink. But Richards *et al.* (2000) show that steep-faced glacier-fed progradational successions in Ireland and Scandinavia have evidence of complex nonlinear dynamics, leading to sedimentation patterns that reflect internal interactions involving delta-front steepness and sediment texture, rather than external forcings.

Valley fills often cannot be linearly related to anthropic sediment supply changes, and thus alluvial records must be interpreted in a nonlinear context. There are multiple responses to a given sediment supply forcing, dependent on the transport capacity. The relationship can be described using a nonlinear catastrophe model (Burrin and Scaife, 1988), but even a general recognition of nonlinear complexity greatly improves the ability to interpret the alluvial record. The review of paleoflood indicators by Knox and Kundzewicz (1997) shows that modest climate changes may have disproportionately large impacts on the magnitude and frequency of extreme floods (a hallmark of nonlinear dynamical instability). This poses obvious limitations for the use of paleohydrological indicators of climate change.

The interpretive advantage of a nonlinear perspective is not always associated with nonlinear complexities *per se*, but such a perspective may result in the development of testable hypotheses. For example, two general competing hypotheses explain the statistical distribution of bed thickness in turbidite sequences in the western Pacific – intrinsic nonlinear dynamics and earthquake triggering. By explicitly testing for nonlinear dynamics, Beattie and Dade (1996) were able to show that the turbidite sequences in the Izu-Bonin basin are consistent with earthquake forcings.

2 Explanation

In some cases complex nonlinear dynamics can provide explanations of phenomena not otherwise explained. In climatology there are numerous examples where nonlinear dynamical instabilities provide the only plausible, or the most widely accepted, explanations for phenomena such as abrupt shifts observed in paleoclimatic proxy data. There are also numerous examples in geomorphology, pedology and hydrology, as summarized elsewhere (Phillips, 1999).

In soil geomorphology, for instance, it is common to observe fundamental variations in soil morphology and stratigraphy over short distances and small areas that are not attributable to any measurable or observable variation in soil-forming factors. In some cases dynamical instabilities and chaos not only provide a plausible explanation for this complex spatial variability, but can be demonstrated with field evidence and linked to specific triggers such as bioturbation or microtopographic variation (Phillips, 1993a, 1997; Phillips *et al*., 1999). Further, in some cases the complex nonlinear dynamics can be linked to specific pedogeomorphic processes such as clay illuviation and its effects on moisture penetration, erosional profile truncation and the growth of eluvial horizons at the expense of adjacent horizons (Phillips, 1993a, 2000; Phillips *et al*., 1999). All the examples cited come from fieldwork in Ultisol landscapes of the North Carolina coastal plain. The ability to link complex nonlinear behaviors to geomorphic processes is also evident in Allison's (1994) review of hillslope processes, which shows that steady state, cyclical and chaotic behavior in regolith evolution is directly linked to the relative rates of bedrock erosion and erosional debris removal.

Another example is the formation of beach cusps, where nonlinear wave/beach interactions not only provide a field-testable hypothesis, but are also capable of explaining cusp formation in some situations where the major competing hypothesis (edge waves) does not apply (Masselink, 1999). This problem illustrates the importance of dealing with nonlinearity on a case-by-case basis. The review of evidence on the nonlinearity versus edge waves hypotheses of beach cusp formation by Coco *et al*. (1999) shows that there is not convincing general evidence for one hypothesis or the other, though the mode of formation can sometimes be identified in particular settings (as in Masselink, 1999).

The general presence of nonlinear relationships (for example, linking sediment transport with velocity, force or power) has always been recognized and utilized in geomorphology. The presence of nonlinear complexities in the form of thresholds and complex responses has long had explanatory power, often manifested outside of the formalisms of nonlinear or systems theory. Thus, it should not be surprising that formalisms incorporating thresholds, complex response, multiple equilibria and more exotic forms of nonlinear complexity should also have explanatory power in the study of landforms.

3 Analytical tools

Nonlinear formalisms and methods may provide tools for understanding, explaining and describing complex systems. Chaotic systems, for example, are sensitive to minor variations in initial conditions and to small perturbations. This is sometimes interpreted to mean that such systems are inherently unpredictable, and for practical purposes indistinguishable from genuinely random systems.

If an apparently random system is shown to be chaotic, this actually poses several advantages. While it does inhibit some forms of predictability and limit the range of forecasts, chaos also by definition implies the presence of underlying deterministic dynamics. Discovering this underlying engine of pseudo-randomness may be an important step to predictability. Further, while chaotic models and equations produce complicated, irregular, patterns that are unpredictable in detail over long times/distances or many iterations, these patterns have several attractive characteristics. First, they are often perfectly predictable a few iterations into the future. Secondly, though the details are irregular and unpredictable, chaotic patterns or series have well-behaved statistical moments. Finally, and by definition, chaos occurs within deterministically defined boundaries: unlike true randomness, all outcomes are not equally possible and the entire phase space is not potentially filled.

For instance, nonlinear models performed better than linear models in forecasting surf zone sediment suspension at Duck, North Carolina (Jaffe and Rubin, 1996). The recurrence patterns of lake-volume fluctuations were shown to be better modeled and forecast by nonlinear models than by classical linear methods of time series analysis (Lall *et al*., 1996; Sangoyami *et al*., 1996). The methods used in these studies capitalized on two important characteristics of chaotic sequences – the ability to predict deterministically a few iterations ahead, and the role of history in conditioning subsequent values of a time series. Neither is possible in a system that is (or is treated as) linear and random. In many cases the unstable growth of small perturbations, but with finite and well-defined limits and aggregate statistical regularity, is reflected in a syndrome of chaotic instability at one scale resolved into orderly, even regular patterns at a broader scale. Studies based on this approach have led to improved models of fluvial, coastal and aeolian bedforms (e.g., Nelson, 1990; Rubin, 1992; Werner, 1995; Rey *et al*., 1995).

Nonlinear dynamical systems theory and methods may provide tools for different types of explanation than are possible or typical otherwise, particularly with respect to analysis of patterns and relationships as opposed to specific entities. There are typically scaling relationships, for example, between measured geologic process rates and the timespans of measurement, such that the longer the timespan of measurement the slower the apparent process rate. This concept is not intuitively difficult for geomorphologists to accept, as geomorphic change is typically episodic, and longer timespans are more likely to encompass periods where little or nothing is happening. Snow (1992) was able to model this discontinuity in the context of uplift and denudation events with a Cantor dust model that reproduces the event clustering preserved in the geologic record. He notes the advantages of this nonlinear, fractal-based approach to this scaling relationship: the Cantor dust model not only gives an adequate explanation of the scaling relationships, but 'turns a perceived problem of disparity in measured process rates into an opportunity to explore the characteristics of earth surface systems', allows quantification of event clustering and process discontinuity that are not easily quantified otherwise and facilitates analysis of situations where the qualities of interest are expressed across a broad range of spatial and temporal scales (Snow, 1992: 193).

4 Modeling and experimental design

Nonlinear complexity raises critical issues for numerical modeling, and for the design of experiments and data collection. Nonlinear systems open up many possibilities for complex behavior that do not exist in linear systems. Where such complexities are possible, they may have serious implications for the generation and interpretation of model results. For instance, models relating the production of soil by weathering to erosional removal, and the feedbacks between them, may produce steady-state, cyclical or chaotic trends, with different parameter values that are all within plausible ranges. Further, a simple decision such as whether to make weathered debris immediately available for removal, or only in the next model iteration, can cause the model to produce qualitatively different results (Phillips, 1993b, 1995).

Nonlinearity also implies a need to collect more data points to define relationships, a lesson geomorphologists seem to have learned long ago. Imagine, for example, that the relationship between wind velocity and sand transport was defined on the basis of two measurements, giving the erroneous perception of a linear association without the critical thresholds and curvilinear relationship we know to exist based on a number of data points at a range of conditions. While this may seem self-evident to most earth scientists, such issues are controversial in related fields. For example, some studies relating vegetation responses to atmospheric carbon dioxide concentration have been criticized for implying linear functions, because the few experimental data points in some studies are incapable of capturing the nonlinearities in that relationship (Korner, 2000).

5 Management, policy and responses

Environmental management goals targeted toward a single stable equilibrium may be inappropriate in landscapes with multiple equilibria. Assumptions of steady-state equilibria in planning and engineering may be inappropriate in many systems characterized by disequilibrium, nonequilibrium, unstable equilibria or multiple equilibria. Evidence of disequilibrium, nonequilibrium, instability and multiple equilibria in geomorphic systems is extensive, and in many cases implications for planning and design are self-evident. Some more explicit discussions in a policy or management context include Gares *et al*. (1994) on geomorphic hazards, Graf (2001) with respect to river restoration, Nathan (1999) on soil salinization and Phillips and Renwick (1996) on erosional degradation of drylands.

Recognition of nonlinearities may allow exploitation of opportunities to change or nudge systems in desired ways. For example, a landscape may be recognized to be near a threshold or to be unstable, such that small changes may be sufficient to switch the system to a preferred alternate state. It may also determine the extent of over- or under-reaction to environmental change, the view of the role of disturbances and the perception of 'typical' or acceptable ranges of system states or trajectories. Perkins and Thomas (1993) discuss this in the context of land degradation in Botswana. Instability in the geomorphic and ecosystems may cause rapid change in response to disturbance, but also rapid (but variable) rates of recovery in different system components. There are multiple equilibria, controlled by several different forcings (grazing, topography, drought cycles). Recognition of this nonlinear behavior has profound implications for human response to land degradation.

Another example is artificially drained pocosin peat bogs of the southeastern USA. These are dynamically unstable with respect to drainage changes, and can never fully recover to pre-artificial-channel states because of the oxidation of a surface peat layer and evaporation from water ponded in ditches and canals. On the other hand, feedbacks within the ditch-and-canal channel system act to rapidly degrade channel conveyance capacity due to sedimentation, bank failures, accumulation of organic debris and vegetation invasion. Belk and Phillips (1993) showed that managers could restore a typical pocosin wetland hydrologic regime by simply abandoning maintenance of the artificial channels, which in two to ten years lose their conveyance capacity to essentially become linear ponds and wet depressions.

III Sources of nonlinearity

Some common general phenomena that produce nonlinearity in earth surface systems can be identified, and the list below is a phenomenological typology. This is necessary because any attempt to identify mechanisms is doomed to scale-contingent semantic debate over what constitutes a basic mechanism, process or causal agent, and what constitutes a response. For instance, at the scale of micro-process mechanics, erosion might be considered a response to fluid dynamical processes. At the scale of landscape evolution, however, erosion is a process, and the responses have to do with the manifestations of erosion. The typology presented here is an attempt to identify archetypes of nonlinearity in geomorphic systems. Thus, hysteresis phenomena are discussed as a phenomenological source of nonlinearity in geomorphology, with full knowledge that in some particular cases hysteresis can be conceptualized as a nonlinear response to mechanisms such as depletion of available sediment. It should also be recognized that the sources discussed here are not necessarily independent, and that nonlinear geomorphic systems may reflect more than one of these sources.

1 Thresholds

Threshold behavior is common in environmental systems, and by definition produces nonlinearity. In simple terms a threshold is the point at which a system's behavior changes. When shear stress is less than that necessary to entrain a given particle, the particle stays put. When that critical shear stress threshold is exceeded, the particle is entrained. This simple example is illustrative of one of the two most common types of thresholds in geomorphology:

1) the ratio of force or power (or some surrogate thereof) and resistance. An example is relationships between velocity or stream power and sediment entrainment, or deposition;
2) the relative rates of linked processes, such as glacial accumulation and ablation.

Geomorphic thresholds may be either intrinsic, and associated with the inherent structure or dynamics of the geomorphic system, or associated with external factors such as climate, tectonics and base level. Good general discussions of thresholds in geomorphology, and the complexities they introduce, are given by Chappell (1983), Schumm (1979, 1991) and Coates and Vitek (1980).

In some cases thresholds can be dealt with effectively without recourse to nonlinear formalisms – geomorphologists have always done this. In other cases, however, thresholds can be directly linked to complex nonlinear dynamics. Hooke and Redmond (1992) analysed changing and stable reaches in English rivers, concluding that thresholds result from complex combinations of factors and do not relate in any simple linear way to the factors generally supposed to control fluvial systems. In paleohydrologic studies of rivers in the Netherlands, Vandenberghe (1995) found no linear response of rivers to climate at any time scale. At the time scale of centuries, the nonlinear response to climate forcing was explicitly linked to thresholds. Muhs (1984) showed how intrinsic thresholds can explain instability in soil development in the absence of environmental change. Examples include minimum levels of sesquioxides to immobilize organic matter in spodic horizons, leaching of carbonates before clay development can occur and some minimum clay mineral ratios before a pedogenic regime dominated by pedoturbation can occur. Divergent self-organization in coastal plain weathering profiles was directly linked by Phillips (2000) in some cases to the balance between thickening of the solum at the weathering front and surface erosion.

Not all thresholds involve force–resistance relationships or rates of linked processes. One example is given by Fitzjohn *et al*. (1998), who show in a gullied semi-arid watershed in Spain that there is a threshold wetness level at which increased hydrologic connectivity causes a nonlinear 'switch' to a state of widespread runoff and erosion.

More generally, it has been argued recently that some nonlinear systems evolve to a 'critical' state, generally characterized by proximity to a threshold. Schumm (1979) argued that as a result of the predominance of thresholds, landforms typically evolve to a condition of incipient instability. Schumm's work thus anticipates recent studies of self-organized criticality, but arrives at similar basic conclusions based on geological reasoning.

2 Storage effects

The storage of mass and energy often introduces lagged nonlinear responses. The presence of Hurst effects and $1/f$ noise in time series of stream discharge and other geophysical time series, for example, can often be explained by storage effects in earth surface systems (Kirkby, 1987; Outcalt *et al*., 1997). Such storage is geomorphically meaningful, and is a more parsimonious explanation than some competing explanations, such as self-organized criticality. In the fluvial sediment system for the Tar River, Phillips (1987) showed that storage effects may determine whether a system is dynamically unstable and chaotic. Knox's (1993) studies of paleoflood geomorphology show that fluvial responses to floods are associated with episodic mobility and storage of sediment, and that this in turn produces fluvial responses that are disproportionately large compared with the hydrologic forcings.

Storage may also be directly related to sensitivity to initial conditions. In an Appalachian drainage basin in Pennsylvania, Troch *et al*. (1994) found that the flood frequency distribution was insensitive to maximum rainfall intensity, but highly sensitive to initial conditions of soil moisture storage.

3 Saturation and depletion

Saturation and depletion effects are responsible for many nonlinearities in biological systems. These effects are associated with the existence of some optimum level of availability of a resource or an input. As availability increases up to this optimum, each unit supplied has an increasing effect. Beyond the optimum, the effect of a unit increase declines, and may even be retarding. The nonlinear response of plants to supplies of water, sunlight, nutrients and CO_2 is an archetypal example. Because of the numerous direct and indirect linkages between organisms and geomorphic processes, it could be argued that this ecological nonlinearity introduces some nonlinearity into geomorphic systems. However, the point can be made independently of reference to biological phenomena.

A simple example is the relationship between moisture availability and oxidation. Up to some optimum moisture content, more moisture equates to more rapid weathering. At some point chemical factors other than moisture limit weathering rates, and further moisture supplies do not increase oxidation. Finally, at saturation, oxidation may be halted, and reversed by reducing reactions. Nonlinear self-organization in lateritic weathering, in some cases associated with saturation and depletion phenomena, is discussed by Nahon (1991). Another example is that of transport- and supply-limited fluvial systems. Increases in stream power, for instance, would result in increased sediment transport up to the point where supply becomes limiting, at which point further increases in stream power have no influence on sediment transport.

In the development of regoliths and weathering profiles, saturation and depletion effects are seen in the relationship between regolith or soil thickness and weathering rates. Starting from fresh rock, up to some maximum increasing soil thickness increases weathering rates, primarily due to moisture storage and biological effects as soil develops. At some critical thickness, moisture and organic matter are no longer limiting, and the rock weathering rate slows down with increasing thickness because the weathering front is increasingly further removed from surface moisture, biotic effects and the atmosphere. This general phenomenon has been shown in several empirical studies (Clément, 1993; Pillians, 1997; Heimsath *et al*., 2000; Gracheva *et al*., 2001). When feedback relationships reflecting a decreasing weathering rate with soil thickness are included in models of regolith evolution and of the balance between weathering and surface erosion, the models typically show dynamical instability and deterministic chaos (Phillips, 1993b; Minasny and McBratney, 1999).

4 Self-reinforcing positive feedback

Positive feedback mechanisms are well-known in geomorphology. Once some features – for example, solutional karst depressions and nivation hollows – begin to develop, they begin to reinforce themselves by accumulating additional water or snow. Basic mathematical and systems theory principles show that an overabundance or dominance of positive feedback produces dynamical instability.

A common geomorphic situation is where initial variations in resistance to weathering or erosion (sometimes quite minor variations) are self-reinforcing. Once a weathering or erosion feature is initiated, the resistance may be further reduced, and/or additional moisture or other denudational agents attracted or stored. Over time, initial variations become increasingly magnified, and evolution is dynamically unstable and divergent.

Twidale (1991) gives seven Australian examples of landscapes in varied tectonic settings where relief has increased over long periods (60 to 100 ma). Twidale links this relief increase to a reinforcement of initial differences in susceptibility to weathering and erosion. Divergent evolution in the form of progressive exaggeration of minor initial differences explains the high relief of Precambrian Charnockites of Southern India and Sri Lanka, according to Gunnell and Louchet (2000) who show a lack of compelling evidence for the competing, conventional explanation based on vertical block-faulting. In the Virginia Piedmont, Stolt *et al*. (1993) found that the lateral variability of particle size and composition in the regolith was greater than that of the parent rock, and linked the difference to differential weathering rates associated with slight variations in the parent rock.

Another example is the instability of wetting fronts and the development of 'fingered flow' even in homogeneous soils with uniform ponded infiltration. Minute, unmeasurable variations in initial moisture or in soil properties create locally increased soil moisture. This, in turn, facilitates more moisture flux, reinforcing the minuscule initial differences and resulting in preferential flow (Liu *et al*., 1994; Ritsema and Dekker, 1994; Ritsema *et al*., 1993). This mechanism, well-known at the event scale, may also result in the formation of minor landforms and major features of weathering profiles, such as sand columns, tubular horizons and extreme local spatial variability in the depth to B-horizons. The mechanisms by which this event-scale hydrologic phenomenon leaves signatures in pedologic and geomorphic development include illuviation effects on moisture penetration, persistence of moisture variations between events, gradual leaching of water-repellant substances in flow fingers and the secondary effects of moisture content on sand erodibility (Dekker and Ritsema, 1994; Pereira and Fitzpatrick, 1998; Ritsema *et al*., 1998; DiCarlo *et al*., 1999).

5 Self-limitation

Curvilinear relationships and discontinuities can also result from self-limiting processes. One example is the depletion of weatherable minerals during chemical weathering, which ultimately slows weathering rates independently of any external influences. Mathematically, at least one self-limiting relationship and a dominance of self-limiting over self-reinforcing feedbacks is a necessary (but not sufficient) condition for stability. However, self-limiting feedbacks can contribute to the overall instability (or stability) of a dynamical system, and certainly result in nonlinearities that may or may not be associated with complex behavior. Torrent and Nettleton (1978) review self-limiting feedbacks in soil formation, including organic matter accumulation in mollisols, clay accumulation in argillic horizons and windows in duripans. Diffusion degradation (downwasting), which is self-limiting because of transport dependency on slope, was directly linked to Hurst phenomena in topography in the spatial domain by Culling (1986), based on a fractal analysis.

The extent to which a process is self-limiting as opposed to limited by another system component is usually directly linked to the way the system is structured or defined. If base level is not included as a system component, for instance, then fluvial incision may be considered self-limiting as downcutting approaches base level. In a system that includes base level as a component, incision would be limited by base level. Either formulation might be appropriate depending on the problem and the spatial and temporal scale.

The relationship between floodplain accretion and flooding frequency is a self-limiting process. In the absence of hydrological change, the higher the floodplain becomes the less often it is flooded. Nanson (1986) showed how, in several Australian rivers, this leads to a cyclic pattern of floodplain creation and destruction. Floodplains accrete by overbank deposition until they rarely flood, and most flows are confined within the banks. Eventually this must cause force–resistance thresholds to be exceeded, flushing out the alluvium and beginning the process anew. Self-limiting processes of biomass production and decomposition play a role in the model of peatland formation of Hilbert *et al*. (2000), which shows multiple equilibria and nonlinear path dependence. While not directly supported with field evidence, the model could explain the tendency of some peatland landscapes to show a bimodal character of either deep or shallow peat (bog or fen), with no intermediate peat thicknesses.

A model of the relationships between infiltration, soil moisture and surface runoff under fixed precipitation input includes self-limited soil moisture storage – at low moisture contents binding pressure limits withdrawals, while in wet conditions porosity and gravity drainage limit storage. Stability analysis of this model suggests that infiltration–excess runoff is unstable and chaotic, such that the most minuscule variations in precipitation intensity, soil moisture or soil hydrologic properties would lead to much larger variations in runoff (Phillips, 1992). This result is supported by several plot studies. The model also suggests that saturation–excess overland flow is stable, a result supported by the fact that Wilcox *et al*. (1991) were unable to find any evidence of chaos in time series of snowmelt runoff.

Self-limitation of weathering due to depletion of weatherable minerals on upper slope segments and higher elevations in the Quebec Appalachians allows altitudinal differences to be maintained (Clément, 1993). Complexity in east Texas weathering profiles is chiefly associated with complex interactions within the weathering system, rather than inherited from parent material inhomogeneity (Phillips, 2001). Self-limiting weathering rates play a key role in the fundamental instability of the weathering system in that study.

There are other examples where analysis in detail of geomorphic systems shows that certain processes or relationships, when considered at a broader scale, are self-limiting. There is a relationship between the elevation and relief of mountain ranges, the corresponding denudation rates and the isostatic compensation to erosional unloading. The interaction between these components is such that uplift is ultimately self-limiting and there are fundamental limits on the height of mountain ranges (Ahnert, 1970, 1984). At the scale of Ahnert's model, uplift is limited by erosion feedbacks but, in the context of a broader-scale crustal evolution model uplift might be appropriately considered self-limiting. Similarly, Reed's (1990) synthesis of research on coastal marsh response to sea-level rise shows that net vertical accretion is limited by feedbacks to hydroperiod (as relative marsh surface elevation increases flooding is less frequent and sedimentation decreases). In models where hydroperiod is not a component, such as a model comparing the rates of wetland sedimentation with sea-level rise, marsh accretion might be depicted as a self-limiting process.

6 Competitive relationships

In biological systems competitive relationships where two organisms or taxa compete for resources may lead to nonlinearities. Often, the mathematical equilibrium between the competitors is unstable, meaning a small change can result in a switch, leading to the complete dominance of one competitor over the other. Analagous relationships in geomorphic systems occur where two system components have mutually limiting interactions. For example, soil erosion may limit vegetation cover, while vegetation inhibits soil erosion. The vegetation–erosion interaction model cited earlier (Thornes, 1985) shows this type of behavior well, and is supported by subsequent field studies (Abrahams *et al.*, 1995; Puigdefabregas and Sanchez, 1996). There is an unstable equilibrium with vegetation and moderate erosion, but any disturbance will push divergence into maximum vegetation/no erosion or eroded/unvegetated patches.

7 Multiple modes of adjustment

In a linear relationship or a linear system, however complicated, there can be just one equilibrium or mode of adjustment associated with a given set of external controls and inputs. Thus, one source of nonlinearity is multiple modes of adjustment (MMA), whereby there are multiple ways that the geomorphic system may adjust to forcings and boundary conditions. The multiplicity of adjustments may arise simply from numerous degrees of freedom in high-dimensional systems, where there are many variables or components that may vary to respond to changes. Multiple modes of adjustment may also be found in low-dimensional systems, however.

Fluvial hydraulic geometry, the study of how changes in imposed flow are accomodated by channels (and vice versa), is a canonical example of MMA. In downstream hydraulic geometry and other considerations of mutual adjustments between flows and channels at the reach or network scale, or where both hydraulic and channel structure variables are considered, there are numerous degrees of freedom for adjustment, leading to multiple complex responses for any given imposed conditions (Hey, 1979; Ferguson, 1986; Miller, 1991a; Yang, 1992). However, even in consideration of at-a-station hydraulic geometry, where only hydraulic variables are considered and there are only five system components, there are MMA and the system is dynamically unstable (Ergenzinger, 1987; Phillips, 1990, 1991; Miller, 1991b). In addition to the studies cited above, MMA in hydraulic geometry can be inferred from the data of Brush (1961) and Simon and Thorne (1996) in the form of variable and sometimes opposite-from-expected changes in velocity, hydraulic radius, width, slope, and friction factor as discharge varies.

8 Self-organization

Self-organization has various and often conflicting definitions, some of which are unrelated to complex nonlinear dynamics, and some of which are subsumed in the categories above. Some forms, such as self-organized criticality (SOC), create nonlinearities as systems evolve toward critical states. One example has been found in paleoenvironmental records in lake sediment cores from Germany (Dearing and Zolitschka, 1999). Evidence of SOC has also been presented for other geomorphic phenomena, including evolution of channel networks and drainage basins, river meandering and braiding, landslides and slope evolution. However, this evidence is either based on models, or on data that exhibit fractal structures, 1*f* noise or other signatures that may arise from SOC or from a number of other (in some cases more geomorphologically plausible) causes.

In its most general sense self-organization refers to the formation of patterns attributable to the internal dynamics of a geomorphic system, independently of external controls or inputs. Because this may offset or intensify the effects of external forcings and boundary conditions, self-organization may be a source of nonlinearity in a system. Some forms of self-organization, such as SOC, unstable finite divergence of instabilities (for instance in the formation of bedforms) and dissipative structures, are explicitly linked to complex nonlinear dynamics.

Huggett (1988) suggested that self-organization via energy dissipation in systems not in thermodynamic equilibrium was a fruitful approach in geomorphology, and a wide variety of subsequent work, in particular based on landscape or channel network evolution models or on the analysis of topographic data, has explored this idea. The most common hypothesis generated, and often confirmed, is that geomorphic systems evolve so as to maximize total energy dissipation (or minimize work), while simultaneously seeking to equalize energy expenditure throughout the system (for example, Rodriguez-Iturbe and Rigon, 1997). This was proposed as a general principle in fluvial systems well before nonlinearity and self-organization became fashionable in geomorphology (Woldenberg, 1969; Kirkby, 1971). Complex nonlinear dynamics arising from energy dissipation away from thermodynamic equilibrium is suggested by Ibañez *et al.* (1994) in their analysis of the co-evolution of fluvially dissected landforms, soils and ecosystems in the Henares River Valley, Iberian Peninsula. Several field-based examples in fluvial systems have been described, involving hydraulic geometry (Simon and Thorne, 1996), channel adjustments (Molnar and Ramirez, 1998) and undulating canyon walls (Wohl *et al*., 1999).

9 Hysteresis

In the most general sense hysteresis occurs where there may be two or more values of a dependent variable associated with a single value of an independent variable. A common example in geomorphology is the relationship between discharge and sediment transport in a flood, where the sediment load is typically higher on the rising limb of the hydrograph than at the same discharge on the falling limb, because of sediment 'flushing' effects. In ecology, hysteresis is often invoked in describing situations where the pathway or trajectory of ecosystem recovery differs from the trajectory of disturbance or deviation. In sedimentary systems, Allen (1974) suggested that lag effects typically produce nonunique trajectories and sequences, which might be characterized as hysteresis.

In many cases hysteresis can be conceptualized as a nonlinear response rather than a source of nonlinear behavior – hysteresis in the discharge versus sediment transport relationship, for example, can be viewed as a nonlinear response to storage or depletion effects. One technique often used to detect and analyse complex deterministic nonlinear dynamics in geomorphic systems is a state- (or phase-) space plot, whereby some indicator of system state at time or increment t is compared with that at time t+1. Connecting these points may produce various loops, which suggest hysteresis at least in the ecological sense mentioned above, where system developmental or evolutionary trajectories do not repeat. Because this phenomenon may have a number of causes, and represents an archetypal form of nonlinear complexity, hysteresis merits an independent entry in this typology, even though in some cases it may represent a nonlinear response to storage, depletion effects or other triggers.

Some examples of observational studies in fluvial geomorphology based on state–space plots that indicate nonrepeating system trajectories include Murray and Paola (1996) and Sapozhnikov *et al*. (1998) on river width variations, Kempel-Eggenberger (1993) on calcium solute concentrations in streams, Liu *et al*. (1994) and Jayawardena and Lai (1994) on stream discharge, and Hooke and Remond (1992) on river planform change.

IV Discussion and research agenda

The nine general sources of nonlinearity described above are summarized in Table 2. Several generalizations are possible at this point.

1) Nonlinearity is common in geomorphology, as well as related areas of geography, geology, pedology, hydrology and ecology. Nonlinearity is not present or relevant in every geomorphic problem and is often ignored – sometimes with no ill effects and sometimes to the detriment of understanding surface processes and landforms.

Table 2 Sources of nonlinearity in geomorphology

Source of nonlinearity	Why is it nonlinear?	Examples (see text for details)
Thresholds	If a threshold exists, then outputs or responses by definition cannot be proportional to inputs or stimuli across the entire range of the inputs	Force versus resistance; relative rates of linked processes such as glacial accumulation and ablation, or precipitation intensity versus infiltration
Storage effects	The addition or removal of mass from storage creates lags and discontinuities in mass balances and input–output relationships	Lags and discontinuities in fluvial sediment storage; Hurst effects in streamflow
Saturation and depletion	The effect of a unit change in an input or forcing varies with respect to some optimum	Effects of moisture availability on weathering rates; effect of soil/ regolith thickness on bedrock weathering
Self-reinforcing, positive feedback	Changes or disturbances promote their own growth and development independently of external forcings	growth of solutional depressions and nivation hollows; enhancement of variations in weathering/ erosion resistance; preferential flow phenomena
Self-limiting processes	Developmental pathways are limited by factors internal to the system, independently of external forcings	Weathering limited by depletion of weatherable minerals; diffusional slope degradation; floodplain vertical accretion; soil moisture storage
Opposing or competitive interactions or feedbacks	Opposing interactions or competitive feedbacks may cause systems to tip or switch abruptly	Vegetation–erosion interactions; indirect geomorphic effects of ecological competition
Multiple modes of adjustment	Because of many degrees of free-dom or simultaneous 'tuning' of several variables, system may take multiple possible configurations in response to a single forcing or set of boundary conditions	Fluvial hydraulic geometry
Self-organization	Some forms of self-organization involve complex adaptations independent of external forcings	Lake sediment records; channel networks; channel cross-sections; soil landscape evolution
Hysteresis	A dependent variable may have two or more values associated with a single value of an independent variable	Discharge versus sediment transport relationships; river channel changes; stream discharge and solute concentrations

2) Nonlinearity opens possibilities for complex behavior that are not possible in linear systems. However, nonlinearity is only one source of complexity in geomorphic systems, and not all nonlinear systems are complex.
3) Complex nonlinear dynamics can be and have been observed and documented in a number of geomorphic systems and phenomena. Nonlinear complexity is a characteristic of real-world landscapes, not just models. In at least some cases, complex nonlinear dynamics can be directly linked to specific geomorphic processes and controls.
4) Complex nonlinear dynamics pose problems and obstacles for some aspects of prediction in geomorphology, but provide opportunities and tools to enhance predictability in other respects.
5) Methods and theories based on or grounded in complex nonlinear dynamics, and an approach to the field that recognizes and confronts nonlinear complexities are useful to geomorphologists. These nonlinear frameworks can explain some phenomena not otherwise explained, provide better or more appropriate analytical tools, improve the interpretation of historical evidence and usefully inform modeling, experimental design, landscape management and environmental policy. It is also clear that no nonlinear formalism (and, as of yet, no other formalism) provides a universal meta-explanation for geomorphology.
6) The sources of nonlinearity in gemorphic systems largely represent well-known geomorphic processes, controls and relationships that can be readily observed. These include thresholds, storage effects, saturation and depletion, self-reinforcing and self-limiting processes, self-organization, hysteresis and multiple modes of adjustment.

The latter point is particularly important. Much earlier work applying complex nonlinear dynamics to geomorphology (including some of my own) was understandably vague in linking nonlinear complexities with observable earth surface phenomena. In part this was because much of the early work involved modeling and simulation and was therefore a step removed from the 'final court of appeal'. Also, a major focus of that phase of research was devoted to simply determining whether chaos (for example) and other forms of nonlinear complexity were likely to be present in geomorphic systems and the extent to which they might provide plausible explanations for some un- or poorly explained phenomena. The expanding of nonlinear research to encompass real-world data and field observations has enabled the field to move beyond invoking general tendencies such as a proclivity for perturbations to persist and grow or evolution toward a critical state.

Geomorphologists studying nonlinear dynamics are no longer limited to identifying the (possible) presence of an underlying strange attractor, whose state space can be described with n (unknown and undefined) variables. We can now go beyond useful but incomplete meta-explanations based on optimality principles. In addition to slow but significant progress in linking complex nonlinear dynamics to geomorphic controls and mechanisms, a typology of nonlinearity in geomorphic systems can be identified, linked in one direction to observable features of form, process and history, and in another to complex dynamics.

These summary points suggest that adoption of a nonlinear perspective and nonlinear tools would be useful for geomorphologists, and in fact ultimately necessary for progress in the discipline. Some more specific research agenda items may also be identified.

First, there should be established *more links between models and observational data*. A mathematical approach and models are likely to always be a significant part of nonlinear studies, and still comprise the majority of papers published on complex nonlinear dynamics. There is a need to better document nonlinear phenomena in field settings. This includes the development of clear, intuitive, concrete examples of nonlinear dynamics – a first step at synthesizing some was attempted here – which illustrate their importance and implications and can thus be communicated to the broader scientific community and the public at large.

Within the observation realm, *more field observations* as opposed to controlled experiments are needed. This includes the need to *develop hypotheses from nonlinear theory which are testable on the basis of observations in nature*. It also includes the need to take advantage of environmental gradients and 'nature's experiments', and to more fully utilize existing observational data. This is probably a greater issue for nonlinear dynamics in environmental science as a whole than in geomorphology, which inevitably and inexorably works its way to ground truth and nature-on-its-own-terms. Nevertheless, given that progress in geomorphology is inextricably linked to that in geophysics, ecology, hydrology, climatology and other fields, it is sometimes necessary for earth scientists to preach the gospel of ground truth, field verification and landscape interrogation.

Assessing predictability is critical in several senses. We need to know the range, accuracy, precision, and uncertainty of predictions, which are all profoundly influenced by nonlinearities. We also need to re-evaluate the goals and meaning of prediction in a nonlinear context. While complex nonlinearities make some types of prediction and forecasting difficult or even impossible, the presence of (for instance) chaos may enable other, new, different predictive methods. There is also a critical need to assess the extent to which unpredictability and uncertainty are inherent in system structures and dynamics, as opposed to being associated with stochastic forcings, large degrees of freedom, and information inadequacies. Nonlinear complexities may offer a new context for predictability – where we recognize that we can perhaps never accurately forecast the time and coordinates of flood scouring or earthquake-induced landslides, but can move toward very accurate and precise identification of synoptic situations where such events are extremely likely or unlikely, and more exact identification of trigger mechanisms.

Complex nonlinear dynamics also dictate increased concern with *landscape sensitivity* (see Thomas, 2001). Knowing that nonlinearity provides a new context for predictability, we must ask what landscapes and systems have higher and lower degrees of predictability, and what types of predictions are feasible. Knowing that systems near thresholds or critical points are subject to large, rapid switches, we should ask what systems are near or approaching thresholds. Knowing that some geomorphic systems are unstable and therefore vulnerable to small perturbations, we should identify such systems, so that we may mitigate effects of 'bad' changes in system state, encourage preferred changes or adjust our perceptions of or response to change.

Finally, I reiterate the point that this research agenda should be problematized from a geomorphic perspective rather than a nonlinear theory perspective. Given that the fundamental sources and manifestations of nonlinearity in geomorphology can be linked to observable earth surface forms, processes and relationships, our natural laboratory – the earth's surface – should be the primary source of ideas in nonlinear geomorphology, as it is in the remainder of the field.

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