7

COMPLEXITY AND NON-LINEAR DYNAMICAL SYSTEMS

Notions of a single equilibrium and stable state were followed by recognition of the existence of multiple stable and unstable states with nonlinearity recognized as common in geomorphology. Such recognition, and also that major changes could occur as a result of relatively minor shifts, gives complex behaviour outcomes that are not predictable in linear systems. Research on complexity theory and nonlinear dynamical systems has included concepts involving chaos theory, dissipative structures, bifurcation and catastrophe theory, and fractal patterning, as well as instability, resilience theory, adaptive cycles, and uncertainty. Such promising concepts are still developing with multidisciplinary centres established to progress further research.

Table 7.2 Principles of Earth surface systems suggested by Phillips (1999)

11 Principles of Earth Surface Systems
• Earth surface systems are inherently unstable, chaotic and self-organizing
• Earth surface systems are inherently orderly
• Order and complexity are emergent properties of Earth surface systems
• Earth surface systems have both self-organizing and non-self organizing modes
• Both unstable/chaotic and stable/non-chaotic features may coexist in the same landscape at the same time
• Simultaneous order and regularity may be explained by a view of Earth systems as complex nonlinear dynamical systems
• The tendency of small perturbations to persist and grow over times and spaces is an inevitable outcome of Earth surface systems dynamics
• Earth surface systems do not necessarily evolve toward increasing complexity
• Neither stable, non self-organizing nor unstable, self-organizing evolutionary pathways can continue indefinitely in Earth surface systems
• Environmental processes and controls operating at distinctly different spatial and temporal scales are independent
• Scale independence is a function of the relative rates, frequencies and durations of Earth surface phenomena

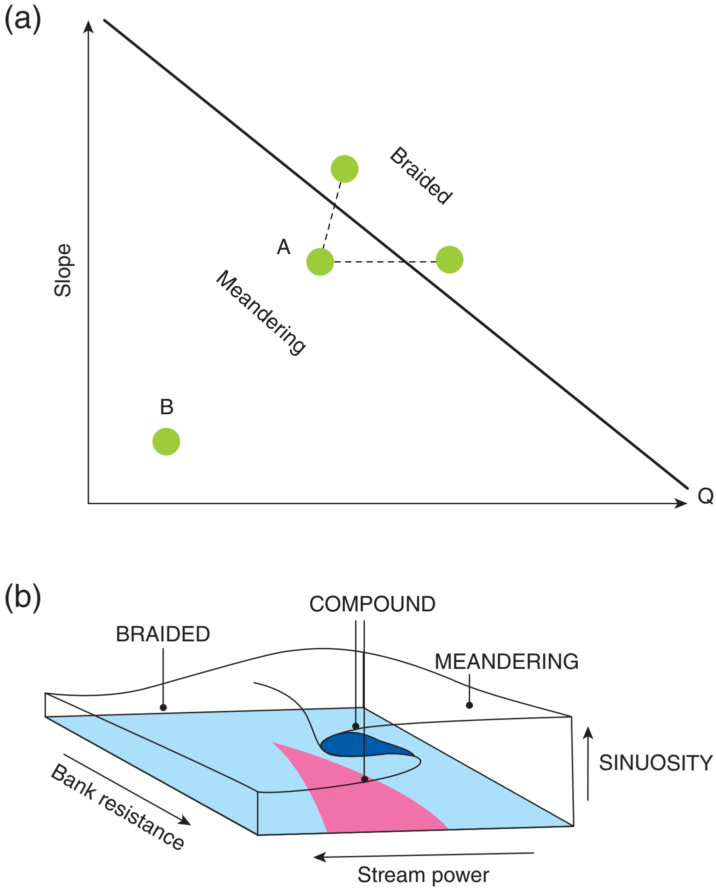

Figure 7.1 (**a**) A discriminant function between braiding and meandering showing an unstable channel at position A and a stable channel at position B. Dashed lines show shifts in slope (vertical) and discharge (horizontal) from A (after Thornes, 2009); (**b**) An example of the cusp catastrophe applied to channel patterns (after Graf, 1988) with permission from Wiley.

Table 7.3 Elements of complexity theory

Theory	Definition	Examples of Use
Catastrophe theory	The mathematical formulations of catastrophe theory, a special branch of bifurcation theory developed by René Thom (1975), can be used to account for sudden shifts of a system from one state to another, as a result of the system being moved across a threshold condition. In geomorphology catastrophe concepts show how small changes in parameters affecting a nonlinear system can cause equilibria to appear or disappear, or to switch from repelling to attracting, giving rise to large changes in the behaviour of the system.	Chappell's (1978) cusp catastrophe model expressing relationships between wave energy, water table height relative to a beach surface, and erosion and accretion.Graf's (1979; 1982) model of the condition at stream junctions in the northern Henry Mountains of Utah.Thornes' (1980) model of bed-load sediment river transport.
Chaos theory	Studies the behaviour of dynamical systems highly sensitive to initial conditions. The manifestations of chaos in landforms and landscapes take the form of divergent vs. convergent evolution (increasing vs. decreasing irregularity), disproportionality vs. proportionality of response to perturbations or initial variations, and the (lack of) geographical consistency or commonality of response (Phillips, 2006, *Geomorphology*).	A conceptual model of landscape evolution. This model, based on nonlinear dynamical systems (NDS) theory, recognizes 10 modes – five stable and five chaotic – of topographic evolution. Together, these modes can accommodate existing theories and models of landscape evolution (Phillips, 1995).
Dissipative structure	Dissipative systems are thermodynamically open systems operating out of thermodynamic equilibrium.	
Fractals	A term coined by Mandelbrot (1975) for patterns which can be subdivided into parts, each of which is nearly a reduced-size copy of the whole.	Applied to river basins by Rodriguez-Iturbe and Rinaldo (1998).

(Continued)

Table 7.3 (Continued)

Theory	Definition	Examples of Use
Self-organizing systems	Self-organization is the spontaneous creation of a globally coherent pattern out of local interactions, typically with non-linear dynamics because of circular or feedback relations between the components (Heylighen, 2001) without control by the environment or an encompassing or otherwise external system.	Aeolian bedforms as the result of self-organizing complex systems (Werner, 1995).
Cellular automaton (CA) approach	A method for modelling a self-organizing system which models continuous space into a series of cells that are usually part of a regular square or rectangular grid.	Simulating the development of nebkhas, blow-outs, and parabolic coastal dunes (Baas, 2007), debris-flow phenomena (D'Ambrosio et al., 2003), the processes operating within river channels driving their geomorphic evolution (Coulthard et al., 2007), the Holocene development of a small upland catchment and the alluvial fan at its base (Coulthard et al., 2002), and the entrainment, transport and deposition of sediments. Reach-scale alluvial dynamics investigated within a landscape evolution model (Van De Wiel et al., 2007).
Panarchy	Conceptual term for a nested set of adaptive cycles that cross multiple spatial and temporal scales. It focuses the need to understand different scales of change in order to explain the causation of modern states, and can be applied in geomorphology.	Potential contribution of geomorphology to tropical mountain development where the panarchy metaphor identifies collapse and reorganization as a common characteristic of socio-economic and biophysical systems (Slaymaker, 2007).
Resilience theory	The capacity of a system to absorb disturbance and reorganize while undergoing change but still retaining essentially the same function, structure, identity, and feedbacks.	Used to reconstruct landscape system behaviour for the past 3,000 years in the Erhai lake-catchment system, Yunnan, SW China, showing the possibility of alternative steady states in the landscape, as expressed by the relationship between land use and erosion in phase space (Dearing, 2008). A period of agricultural expansion ~1400 cal. BP triggered rapid gully erosion that continued to accelerate for 600 years until the formation of a 'steady' eroded landscape state that has existed since ~800 cal. BP.

Theory	Definition	Examples of Use
Uncertainty	An ‘information deficit’ to be resolved, rather than an inherent product of conducting research, some arising from system complexity, non-linearity, and space-time variability (Brown, 2010). (See Chapter 19.)	Influence of debris flow mobility relationships on prediction of inundated areas (Simoni et al., 2011).
Complexity theory	The study of complex adaptive systems which have been defined as ‘a collection of individual agents with freedom to act in ways that are not always totally predictable, and whose actions are interconnected so that one agent’s actions changes the context for other agents’.	Functioning and evolution of landscape systems (Favis-Mortlock and de Boer, 2003).
Emergence	Situation arises that could not be predicted from the components and their interaction.	(Phillips, 1999; Favis-Mortlock, 2013).

RELEVANT ARTICLES IN *PROGRESS IN PHYSICAL GEOGRAPHY:*

French, J.R. and Burningham, H. (2009) Coastal geomorphology: trends and challenges, *Progress in Physical Geography,* 33: 117–129.

Güneralp, I. and Marston, R. A. (2012) Process–form linkages in meander morphodynamics: bridging theoretical modeling and real world complexity, *Progress in Physical Geography,* 36: 718–46.

Phillips, J.D. (2009) Changes, perturbations, and responses in geomorphic systems, *Progress in Physical Geography,* 33: 17–30.

UPDATES

Two concisely expressed opinions as to our expectations of complexity or simplicity appeared in *Nature* in 2011. Paola made the case for requiring simplicity as an aid to understanding, whilst Leeder pointed to the continuous flux of nature producing inherent complexity:

Paola, C. (2011) In modelling, simplicity isn't simple, *Nature*, 469: 38.

Leeder, M. (2011) Complexity and the memory of landscape, *Nature*, 469: 39.

More recently, Murray et al. (2014) considered the identification of 'cause' in complex systems:

Murray, A.B., Coco, G., and Goldstein, E.B. (2014) Cause and effect in geomorphic systems: Complex system perspectives, *Geomorphology*, 214: 1–9.

Recent applications of graph theory concepts and methods show how graph theory is especially well suited to analysis of inherent complexity, exploration of very large data sets, focus on spatial fluxes and interactions as discussed by:

Phillips, J.D., Schwanghart, W. and Heckmann, T. (2015) Graph theory in the geosciences, *Earth-Science Reviews*, 143: 147–60.

A commentary presenting recent contributions that have the potential to advance the use of complexity in geomorphology is: Temme, A.J.A.M., Keiler, M., Karssenberg, D. and Lang, A. (2015) Complexity and nonlinearity in earth surface processes – concepts, methods and applications, *Earth Surface Processes and Landforms*, 40: 1270–74.

A challenge for current observational networks is to capture the often fast changing and nonlinear behaviour of ecosystems, particularly when studying system interfaces and coupled ecological, hydrological, geomorphological and biogeochemical processes, demanding novel, adaptive approaches in real-time monitoring and research. A paper focusing on real-time ecohydrological research is: Krause, S., Lewandowski, J., Dahm, C.N. and Tockner, K. (2015) Frontiers in real-time ecohydrology – a paradigm shift in understanding complex environmental systems, *Ecohydrology*, 8: 529–37.

Analysis of the role of the geomorphological complexity factor on landslide susceptibility models is achieved by attempting a preliminary procedure for generating a thematic map, representing the spatial distribution of complexity factor in a specific study area: Spilotro, G. and Pellicani, R. (2015) Geomorphological complexity in landslide susceptibility modelling, engineering geology for society and territory – *Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation*, pp. 415–19.

von Elverfeldt, K., Embleton-Hamann, C. and Slaymaker, O. (2016) Self-organizing change? On drivers, causes and global environmental change, *Geomorphology*, 253: 48–58. Suggests how complexity theory and self-organizing systems provide important caveats in relation to studies that attribute all environmental change to external drivers and that existing geomorphological concepts such as singularity, extrinsic and intrinsic thresholds, and sensitivity can be accommodated within the concept of self-organization.

Reviewing how state-and-transition models (STMs) can provide a unifying framework to address questions about socio-biophysical landscape evolution and showing how they have been used to analyze a variety of ecological, geomorphic, and hydrological transitions in complex biophysical landscapes and indicating how they can be expanded to accommodate critical investigations of the social dynamics underpinning landscape change: Van Dyke, C. (2015) Boxing daze – using state-and-transition models to explore the evolution of socio-biophysical landscapes, *Progress in Physical Geography*, 39: 594–621.

In relation to the development of catchment models a discussion of the vital role of system complexity as an appropriate basis for the classification framework and the potential of nonlinear dynamics, networks, and other modern concepts of complex systems science for assessing system complexity is: Sivakumar, B., Singh, V.P., Berndtsson, R. and Khan, S.K. (2015) Catchment classification framework in hydrology: Challenges and directions, *Journal of Hydrologic Engineering*, 20: A4014002.

Demonstrating how one component of geomorphic complexity results from spatial heterogeneity in river corridors this article considers measures of complexity used although there is no single, widely used metric of complexity and public attitudes continue to emphasize attractive appearance: Wohl, E. (2016) Spatial heterogeneity as a component of river geomorphic complexity, *Progress in Physical Geography*, 40: 598–615.

A review of the concept of river sensitivity which provides examples to demonstrate how the concept could be reshaped and used for analyses at landform, reach and catchment scales is: Fryirs, K. A. (2017) River sensitivity: a lost foundation concept in fluvial geomorphology, *Earth Surface Processes and Landforms*, 42, 55–70. A special issue of the journal *Geomorphology,* based on conference papers, explored another concept, that of connectivity: E.Wohl, F.J. Magilligan and S.L. Rathburn (eds) (2017) Connectivity in Geomorphology, from Binghamton (2016) *Geomorphology,* 277: 1–282. The papers look at the complex pathways followed by materials, energy flows and organisms in geomorphological systems through a number of key themes.

Arguing that focus on self-organization provides important caveats in relation to studies that attribute all environmental change to external drivers and that a multitude of independently existing geomorphological concepts – including singularity, extrinsic and intrinsic thresholds, and sensitivity – can be well framed and combined within the concept of self-organization, this paper also has implications for equifinality, complexity theory and global environmental change: Von Elverfeldt, K., Embleton-Hamann, C. and Slaymaker, O. (2016) Self-organizing change? On drivers, causes and global environmental change, *Geomorphology*, 253: 48–58.