Toward understanding complexity of sediment dynamics in geomorphic systems

Peng Gao[1]*, James R. Cooper[2], and John Wainwright[3]

[1]Department of Geography, Syracuse University, Syracuse, NY 13244 USA
[2]Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Liverpool, L69 7ZT, UK
[3]Durham University, Department of Geography, Science Laboratories, South Road, Durham, DH1 3LE, UK

*corresponding author: pegao@maxwell.syr.edu

Processes of sediment detachment, transport, and deposition vary over a wide range of temporal and spatial scales (Yair and Kossovsky, 2002; Collins and Walling, 2004; Orwin and Smart, 2004; Vericat and Batalla, 2006; Gao, 2008; Smith et al., 2011; Jones and Preston, 2012; Wirtz et al., 2013; Wainwright et al., 2015). Spatially, sediment load measured at one spatial scale of a watershed is not representative of that at another (FitzHugh and Mackay, 2000; Parsons et al., 2004; de Vente and Poesen, 2005; Van Dijk and Bruijnzeel, 2005). Temporally, the cumulative effects of these complex processes over long time periods give rise to various landforms in geomorphic systems that have long challenged scientists in revealing their evolutional history (Gilbert and Dutton, 1877; Gilbert, 1909; Carson and Kirby, 1972). In recent decades, intensified anthropogenic activities, such as agriculture, urbanization, channelization, and/or dam removals (Gomi et al., 2005; Estrany et al., 2009; Warrick et al., 2015) and the increased likelihood of extreme weather (Zhang et al., 2013; Foulds et al., 2014; Jena et al., 2014) make it more difficult to characterize sediment dynamics at different temporal (event, seasonal, annual, or decadal) and spatial (plot, reach, or subwatershed) scales (Walling and Zhang, 2004; Owens et al., 2005; Wilkinson and McElroy, 2007).

The complexity of sediment dynamics is generally reflected in the variable processes and environmental heterogeneity that dominate at different scales (Fryirs, 2013). As such, the true sediment transport rates, loads, and yields are more relevant to localized and unsteady processes at different spatial and temporal scales that can often not be characterized by traditionally used spatial- and/or time-averaged hydraulic variables and morphologic indices (Yager et al., 2012; Segura and Pitlick, 2015). Therefore, existing theories on sediment initiation, transport, and deposition—based on these averaged quantities—often poorly quantify sediment dynamics in various geomorphic systems. Consequently, it is imperative to explore new perspectives and ideas that may more efficiently link the complexity of sediment dynamics over various spatial and temporal scales.

The 49th Binghamton Geomorphology Symposium (BGS), held 5–7 October 2018, was in response to this need with a focused theme of ‘Sediment complexity within geomorphological systems’. The BGS has been held annually since 1970 (Sawyer et al., 2014). The fundamental goal of these symposia has been to discuss and advance timely topics in geomorphology. In the past 48 symposiums (Table 1), half of them have involved, to varying degrees, topics related to sediment dynamics. Five of them concentrated on five traditional subdisciplines in geomorphology (1973, 1974, 1980, 1991, and 1998), and erosion and sediment transport was an essential part of each. Seven of them have discussed geomorphic processes from the theoretical perspective (1975, 1978, 1992, 1993, 1996, 2007, and 2016). Chronologically, these symposia reflect the evolution of geomorphological theories in the past four decades. In particular, the last two (i.e., 2007 and 2016) reflect recent transformations in geomorphic theories from early pure physical and/or (relatively) simple interaction between nature and human beings to integrated coupling among physical, ecological, and social aspects. The 49th BGS carried on the intellectual merit of past symposia through its strong influence on the scientific community. Novel ideas and approaches of resolving these challenges emerging from the 2018 BGS promote multidisciplinary collaborative research on sediment complexity.

Partially derived from this symposium was this virtual special issue, which includes a collection of 11 peer-reviewed papers addressing sediment complexity using a variety of methods such as field survey, computer simulation and modeling, flume experiments, fingerprinting, and statistical analysis. The topics of these papers involve (i) mechanics of bedload transport at short or long temporal scales; (ii) modeling sediment-transport processes over multiple spatial and temporal scales; (iii) characterization of channel morphologic response to natural processes and anthropogenic activities; and (iv) characterizing sediment dynamics in larger spatial scales and longer temporal scales using models of reduced complexity. We summarize these papers in two categories. The first includes 8 papers showing various types of sediment complexity; the second contains 3 papers using simplified methods to characterize key processes of sediment complexity.

Bedload is transported by hydraulic processes in river flows. Although shear stress has been recognized as one of the fundamental hydraulic variables controlling bedload movement, numerous studies have confirmed that bedload equations based on reach-averaged (dimensionless) shear stress not only have limited abilities in predicting bedload in different flume experiments and rivers but also can generate large errors in the same river in which these equations were developed. Building upon this knowledge, Yager et al. (this issue) demonstrated that spatially variable near-bed shear stress is better correlated with bedload flux than the single-value reach-averaged shear stress. Nonetheless, near-bed shear stress may be calculated using velocity profiles, Reynolds stresses, or flow turbulence. The comparative analysis of Yager et al. (this issue) showed that near-bed shear stresses computed from velocity profiles had the best correlation with the associated local bedload fluxes, though the predicted bedload fluxes were still markedly different from the measured ones. This study suggested that velocity-based, near-bed shear stress is still insufficient to capture the spatially and temporally variable hydraulic processes controlling bedload transport. A different type of complexity in bedload transport was addressed by An et al. (this issue). Most gravel-bed rivers have typical bi-mode bed materials: coarse grains in the range of gravels and cobbles, and finer grains that are often sands and silts. Thus far, the mobility of bed surface layer is well known to increase by increased supply of sand. However, its long-term effect is difficult to measure directly. An et al. (this issue) examined this effect by attempting to explain the massive bed degradation in the Shi-ting River, Sichuan Province, China. Using a one-dimensional river morphodynamic model, they simulated riverbed response to the increased amount of sand delivered to the channel after the 2008 Wenchuan Ms. 8.0 earthquake over multiple temporal scales. Based on the measured bed degradation rate over 7 years after the earthquake, the authors concluded that sand augmentation could encourage bed degradation by reducing the critical shear stress for the initiation of bed surface materials. This mechanism is quantitatively embodied in the bedload transport equation developed by Wilcock and Crowe (2003) as a term called reference shear stress, which captures the well-known hiding effect in gravel-bed rivers (Einstein and Chien, 1953; Egiazaroff, 1965; Gomez, 1983; Andrews and Parker, 1987; Sutherland, 1987; Lisle and Madej, 1992; Montgomery et al., 2000). However, An et al. (this issue) also recognized that long-term bed degradation in gravel-bed rivers can only be partially explained by this mechanism. Mao (this issue) examined the impact of flood history on bedload-transport rates using a series of carefully designed flume experiments. These flume experiments used different hydrograph sequences and compared magnitudes of the bedload flux produced by these sequences. Mao (this issue) showed that bedload-transport rates produced by a given hydrograph under constant sediment supply are not only controlled by the magnitude and duration of this hydrograph but also affected by the characteristics of its previous hydrograph.

This ‘memory’ of sediment dynamics manifests the complexity of sediment dynamics over temporal scales.

Sediment dynamics is directly involved in migration processes of meandering rivers by affecting channel morphology in a variety of ways. Among the debates is whether the processes controlling bar development in meander channels are linear or nonlinear (Hooke, 2013). Nelson and Morgan (this issue) provided new insight by investigating formation and development of gravel bars under variable water discharges and sediment supply rates in a laboratory flume within a meandering channel of mixed materials of coarse sand and gravels. Their results suggest that rather than causing downstream migration of the developed alternate bars, unsteady flows and variable sediment supply mainly led to variations of bar sizes, which subsequently control bedload transport rates. Yet, the existing linear bar theory could not capture these processes as the width-to-depth ratios of the created meander channel were lower than is required by the theory.

An essential process of meander migration is cutoff. While chute cutoff has been widely studied through in situ measurement, flume experiments, and modeling simulation, neck cutoff has rarely been examined mainly because it is hard to observe in natural meandering rivers and to reproduce in laboratory flumes. Li et al. (this issue) successfully triggered neck cutoff in a predesigned highly sinuous meandering channel with a mobile bed and uniformly sized sands in a laboratory flume. By analyzing neck narrowing processes dominated by local bank erosion, they reveal that while neck cutoff was promoted by progressive bank-erosion processes, it finally initiated seepage-based bank collapse owing to the cross-neck hydraulic gradient caused by water level difference between the upstream and downstream sides of the neck. They conclude that sediment dynamics characterizing local bank erosion processes was insufficient to explain the occurrence of neck cutoff.

The complexity of interaction among processes controlling sediment dynamics across multiple spatial and temporal scales is demonstrated in the following papers. Suspended sediment transport through an entire watershed is commonly determined by establishing sediment rating curves. Although factors that may undermine the predictability of these curves have been well documented (Gao, 2008), such as effects of hysteresis, the fundamental assumption that the relationship between water discharge and suspended sediment loads is stable over time has not been systematically verified. Gray (this issue) sought to test this assumption by examining the temporal dependence of these relationships for small rivers in the U.S. west coast area. Using data recorded from 24 gauging stations in these rivers for more than a decade, he found that in most of the rivers a persistent relationship only existed for an average period of 8.6 years, beyond which the relationship was of the long-term nonstationary nature. Gray (this issue) showed that if this relationship were used to predict long-term suspended sediment loads, the error could be one order of magnitude.

Spatial complexity of sediment dynamics is often embodied by intricate pathways of sediment movement among connected compartments of geomorphic systems. Wittmann (this issue) studied the long-term sediment variation in lower Amazon floodplains using the fingerprinting method based on meteoric cosmogenic ^{10}Be and the ^{10}Be/^{9}Be ratio where ^{9}Be is the mobilized fraction of ^{10}Be. Her results showed that sediment stored in the floodplains was controlled by seasonal cyclic floods that brought sediment from upstream sources to the floodplains. However, present floodplain sedimentation was well-mixed by multiple cycles of storage and remobilization, making disentangling of individual sediment sources very difficult, if not impossible. Viparelli et al. (this issue) examined morphologic responses of tidal channels under the influence of flow hydrodynamics and base-level changes. Using a one-dimensional model, they modeled the effects of sediment with nonuniform sizes on channel morphologic adjustment. Their modeling revealed that combination of sinusoidal tidal forcing with constant input of sand from the ocean results in cyclic deposition in such channels. This finding provided a base for further quantifying the possible impact of sea-level rise on tidal channels.

A common feature of these papers on complex sediment dynamics is that processes controlling sediment dynamics in any geomorphic system are so complex that they cannot be quantified by classic theories or single mathematical equations. The following two studies attempted to provide opposite cases. Czuba (this issue) argued that the key channel morphologic responses to the complex sediment connectivity throughout the network of rivers within a large watershed may be effectively characterized under a framework represented by a physically based, mixed-sized sediment transport model. He showed that this simplified one-dimensional model may capture some key processes, such as reaches dominated by sediment aggradation and segments controlled by locally decreased transport capacity that affects downstream sediment delivery. Thus, the model provides a framework for further understanding complex sediment dynamics over larger spatial scales. Berni et al. (this issue) examined channel response over relatively short periods to the decreased sediment transport rates owing to bed armoring and development of bedforms using a model with reduced complexity. Their analysis showed that a characteristic time for the channel to reach equilibrium may be identified and that this time is affected by five parameters: the dimensionless bed shear stress, the ratio of dimensionless bed shear stress ratio to its critical value for inception of movement, the Reynolds particle number, the standard deviation of sediment distribution, and the width-to-depth ratio. Briant et al. (this issue) showed, using a case of modeling long-term climatic effect on river sediment adjustment, that the relatively simple model may be very useful in examining more complex processes of sediment dynamics in natural rivers.

Among 11 papers included in this virtual special issue, 8 demonstrated a variety of sediment complexity in geomorphic systems. These studies continuously accumulate examples of complex sediment connectivity that transfers in various integrated ways sediment across different sources and sinks over different spatial and temporal scales (Bracken et al., 2015). It is foreseeable that in the future more specific cases on the complexity of sediment dynamics will be reported in scientific community. Theoretically, new ideas and strategies are needed to quantify and model all kinds of sediment complexity efficiently. Yet, developing them confronts a fundamental challenge: how to integrate appropriately different processes dominating sediment dynamics at different spatial and temporal scales. Quantifying these processes require different levels of detail at different spatial and temporal scales (Harvey, 2002; Larsen et al., 2014). Use of models with reduced complexity to capture the dominant processes at a given temporal (decades or centennial) or spatial scale (a hillslope section, river reach, or watershed), as exemplified in the 3 studies included in this virtual issue, has been successful in many cases (Hunter et al., 2007; Murray, 2007; Nicholas, 2010). Unfortunately, no general rules to determine how much complexity may be reduced in a given geomorphic system have been established. The current status of our understanding of sediment complexity calls for more research on these general rules if they exist. A recently developed multiscalar framework based on near-census developments (Wheaton et al., 2015; Pasternack and Wyrick, 2017) appears to be a promising solution. We believe that more studies in the two apparently opposite directions illustrated by the 11 papers in this virtual issue will foster more new approaches to constructing various multiscalar frameworks for determining the complexity of sediment dynamics in geomorphological systems.

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Table 1. List of all Binghamton geomorphology symposia.

Title	Editor(s)	ISBN
1. Environmental Geomorphology (1970)	D.R. Coates	Oct. 1970***
2. Quantitative Geomorphology (1971)	M. Morisawa	Oct. 1971***
3. Coastal Geomorphology (1972)	D.R. Coates	0-045-51038-5
4. Fluvial Geomorphology (1973)	M. Morisawa	0-045-51046-6
5. Glacial Geomorphology (1974)	D.R. Coates	0-045-51045-8
6. Theories of Landform Development (1975)	W.N. Melhorn and R.C. Flemal	0-686-10458-7
7. Geomorphology and Engineering (1976)	D.R. Coates	0-045-51040-7
8. Geomorphology in Arid Regions (1977)	D.O. Doehring	0-045-51041-5
9. Thresholds in Geomorphology (1978)	D.R. Coates and J.D. Vitek	0-045-51033-4
10. Adjustments of the Fluvial System (1979)	D.D. Rhodes and E.J. Williams	0-840-32108-2
11. Applied Geomorphology (1980)	R.G. Craig and J.L. Craft	0-045-51050-4
12. Space and Time in Geomorphology (1981)	C.E. Thorn	0-045-51056-3
13. Groundwater as a Geomorphic Agent (1982)	R.G. LeFleur	0-045-51069-5
14. Models in Geomorphology (1983)	M.J. Woldenberg	0-045-51075-X
15. Tectonic Geomorphology (1984)	M. Morisawa and J.T. Hack	0-045-51098-9
16. Hillslope Processes (1985)	A.D. Abrahams	0-045-51102-0
17. Aeolian Geomorphology (1986)	W.G. Nickling	0-045-51133-0
18. Catastrophic Flooding (1987)	L. Mayer and D. Nash	0-045-51,142-X
19. History of Geomorphology (1988)	K.J. Tinkler	0-045-51138-1
20. Appalachian Geomorphology	T.W. Gardner and	0-444-88326-6

(1989)	W.D. Sevon	
21. Soils and Landscape Evolution (1990)	P.L.K. Knuepfer and L.D. McFadden	0-444-88692-3
22. Periglacial Geomorphology (1991)	J. Dixon and A. Abrahams	0-471-93342-2
23. Geomorphic Systems (1992)	J.D. Phillips and W.H. Renwick	0-444-89809-3
24. Geomorphology: The Research Frontier and Beyond (1993)	J.D. Vitek and J.R. Giardino	0-444-89971-5
25. Geomorphology and Natural Hazards (1994)	M. Morisawa	0-444-82012-4
26. Biogeomorphology, Terrestrial and Freshwater Systems (1995)	C.R. Hupp, W.R. Osterkamp, A.D. Howard	0-444-81867-7
27. The Scientific Nature of Geomorphology (1996)	B.L. Rhoads and C.E. Thorn	0-471-96811-0
28. Engineering Geomorphology (1997)	J.R. Giardino, R.A. Marston, M. Morisawa	0-444-50301-3
29. Coastal Geomorphology (1998)	P.A. Gares and D.J. Sherman	Nov. 2002*
30. Geomorphology in the Public Eye: Policy Issues and Education (1999)	P.L.K. Knuepfer and J.F. Petersen	Oct. 2002*
31. Integration of Computer Modeling and Field Work	J.F. Shroder, Jr. and M.P. Bishop in Geomorphology (2000)	0-444-51532-1
32. Mountain Geomorphology (2001)	D.R. Butler, S.J. Walsh, G.P. Malanson	0-444-51531-3
33. Dams and Geomorphology (2002)	P. Beyer	0-444-52231-X
34. Ice Sheet Geomorphology (2003)	P.L.K. Knuepfer, J. Fleisher, D.R. Butler	April 2006*
35. Weathering and Landscape Evolution (2004)	A. Turkington, J. Phillips, S. Campbell	0-444-52031-7
36. Geomorphology and Ecosystems (2005)	M. Doyle, M. Thoms, C. Renschler	Sept. 2007**

37. The Human Role in Changing Fluvial Systems (2006)	L.A. James and W.A. Marcus	Sept. 2006**
38. Complexity in Geomorphology (2007)	A.B. Murray and M.A. Fonstad	Nov. 2007**
39. Fluvial Deposits and Environmental History (2008)	P. Hudson, K. Butzer, T. Beach	Sept. 2008**
40. Geomorphology and Vegetation: Interactions, Dependencies, and Feedback Loops (2009)	W.C. Hession, T. Wynn, L. Resler, J. Curran	April 2010**
41. Geospatial Technologies and Geomorphological Mapping (2010)	L.A. James, M.P. Bishop, S.J. Walsh	Jan. 2012**
42. Zoogeomorphology and Ecosystem Engineering (2011)	D.R. Butler and C.F. Sawyer	July 2012**
43. The Field Tradition in Geomorphology (2012)	C.J. Legleiter and R.A. Marston	Oct. 2013**
44. Coastal Geomorphology & Restoration (2013)	N. Jackson, K. Nordstrom, R. Feagin, W. Smith	Oct. 2013**
45. Planetary Geomorphology (2014)	D. Burr and A. Howard	July 2015**
46. Experimental Geomorphology (2015)	S.J. Bennett, P. Ashmore, C. Mckenna Neuman	Sep. 2015**
47. Connectivity in Geomorphology (2016)	E. Wohl, F. Magilligan, S. Rathburn	Jan. 2017*
48. Resilience and Bio-Geomorphic Systems (2017)	D. Butler, J. Julian, K. Meitzen, M. Thoms	Mar. 2018*
49. Sediment Complexity in Geomorphological Systems (2018)	P. Gao, J. Cooper, J. Wainwright	
50. 50 Years of Geomorphology at the BGS (2019)	J. Janke, C. Houser, J.R. Giardino, J. Vitek	

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