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Advances and challenges in meandering channels research

İnci Güneralp [a,*], Jorge D. Abad [b], Guido Zolezzi [c], Janet Hooke [d]

[a] *Department of Geography, Texas A&M University, TX, USA*
[b] *Department of Civil and Environmental Engineering, University of Pittsburgh, PA, USA*
[c] *Department of Civil and Environmental Engineering, University of Trento, Trento, Italy*
[d] *Geography, School of Environmental Sciences, Liverpool, University of Liverpool, UK*

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ABSTRACT

Meandering channels is a vast research field, spanning a broad variety of time and space scales, environmental domains, and conceptual and methodological approaches. This paper serves as an introduction to this special issue of Geomorphology "Meandering Channels", which addresses the need for sustained scientific dialogue on the dynamics of meandering channels. In an effort to place this issue in the broad context of this rapidly changing and advancing research field, we begin by discussing the motivation behind this issue. Then, we continue by summarizing the main novel research contributions of each paper. Finally, we conclude by proposing five major research directions that directly develop from the ensemble of the scientific contributions to this special issue. These research directions emphasize the critical importance of the coupling of near-bank geomorphic and flow processes; the characterization of co-evolution of meandering rivers and their floodplains; the need to improve linkages between meandering rivers research and river management and restoration; the potential of expanding laboratory-based research; and the integration of holistic and reductionist approaches.

1. Introduction

The term "meander" originates from the Büyük Menderes River, which rises in west central Turkey and reaches the Aegean Sea east of Milet, the ancient Ionian city of Miletus. This winding river was known to the ancient Greeks as *Maíandros* (Latin *meaender*) (Lewis and Short, 1922; Strabo, 1924). Use of the term has subsequently evolved to describe anything winding in form, including decorative patterns in art and architecture. Meandering is a common planform of rivers and of submarine channels.

Meandering river channels are dynamic landforms that migrate over floodplains. The migration of meandering rivers results from interactions among flow, sediment transport, and channel form that create complicated sedimentary structures and lead to the evolution of channel planform over time (Seminara, 2006). The morphodynamics of meandering river channels play an important role in sedimentation patterns and processes (e.g., Nanson and Beach, 1977; Howard, 1992; Sun et al., 1996; Gilvear et al., 2000), and hydrological and ecological processes (e.g., Salo et al., 1986; Ward et al., 2002) in floodplain environments. Interest in the dynamics of meandering river channels is scientific and includes concerns related to river engineering and management, such as flood control, navigation, bank erosion, and the protection of land and infrastructure. Meandering river processes are also important in the understanding of the functions of river–floodplain ecosystem as well as human impacts on these functions that can degrade water quality, disrupt river–floodplain connectivity, and diminish aquatic-habitat health and diversity (e.g., Brookes and Shields, 1996; Lagasse et al., 2004; Piégay et al., 2005; Gurnell et al., 2006; Kondolf, 2006; Güneralp and Rhoads, 2009a).

Research on meandering rivers has mainly attempted to explain the morphodynamic evolution of meandering rivers governed by the interactions among water flow, sediment transport, channel planform, and bed morphology. Meandering rivers have drawn considerable attention from a large group of researchers in various fields, ranging from fluvial geomorphology (e.g., Leopold and Wolman, 1960; Hooke, in press) to fluid mechanics and morphodynamics (e.g., Callander, 1978; Ikeda et al., 1981); from river engineering (e.g., Jansen et al., 1979; Elliot, 1984) to petroleum engineering (e.g., Henriquez et al., 1990; Swanson, 1993) to landscape ecology and river restoration (e.g., Greco and Plant, 2003; Kondolf, 2006). The scope of research also encompasses a broad range of spatial scales, from the detailed studies of flow properties at the scale of turbulent eddies (e.g., Blanckaert and de Vriend, 2003) to investigations of the evolution of meander trains (i.e., series of meander bends) over the entire length of an alluvial floodplain (e.g., Gautier et al., 2007). Similarly, studies on river meandering vary in temporal scale, ranging

* Corresponding author.
E-mail addresses: iguneralp@geos.tamu.edu (İ. Güneralp), jabad@pitt.edu (J.D. Abad), guido.zolezzi@ing.unitn.it (G. Zolezzi), Janet.Hooke@liverpool.ac.uk (J. Hooke).

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from the response to a single channel-forming event (Hooke, 2004) to the evolution of floodplains over millennia (e.g., Howard, 1992; Sun et al., 1996; Camporeale et al., 2005; Frascati and Lanzoni, 2009) (Table 1). Although substantive progress has been made, further research is required to achieve a comprehensive understanding of the bio-morphodynamics governing the evolution of meandering channels at different scales and in a variety of environmental domains. The processes governing these dynamics result from the interaction among turbulent river flow, sediment transport, bank erosion mechanisms (e.g., Mosselman, 1998; Darby et al., 2002; Duan and Julien, 2005, and planform morphology (e.g., Parker et al., 1983; Olesen, 1984; Zolezzi and Seminara, 2001; Abad and García, 2009a). Spatial variability in the erosional resistance of floodplain environments is an important external factor that influences the dynamics of meandering (Güneralp and Rhoads, 2011), including the effects of riparian vegetation (e.g., Perucca et al., 2007), the sedimentology of river deposits (e.g., Howard, 1992; Sun et al., 1996; Hudson and Kesel, 2000) and the geological structure of the floodplain landscape (e.g., Nicoll and Hickin, 2010).

Table 1
Scope of research in meandering channels.

Main category	Sub-category	Definition
Environmental domain	Terrestrial	River channels
	Submarine	Channels forming in depositional submarine fans in deep ocean
	Extraterrestrial	Channels forming on other planetary landscapes
Study focus	Flow–bed	Interactions between flow and bed topography
	Banks	Interactions between flow and banks
	Planform change	Change in channel planform of meander train (i.e., a series of meander bends)
	Management	Management and/or restoration of meandering rivers and the floodplains
	Vegetation	Interactions between channel morphodynamics and in-channel and/or floodplain vegetation
	Habitat	In-channel and/or floodplain habitat assessment and management/restoration/conservation
Space scale	Width	Cross-section or channel-width
	Bend	One meander bend *or* a few meander bends, including meander wavelength scale
	Reach	Meander train (series of bends)
	Floodplain	Several reaches, including meander belt scale
Time scale	Equilibrium	Flow–bed topography is at equilibrium with a given planform geometry — a time scale longer than that of turbulent eddies and shorter than that of bed and planform evolution
	Event	One or a few events causing change in bed morphology
	Engineering	Time scale of planform evolution before cutoffs occur — generally, decades for rivers and a few hours in laboratory flumes
	Geological	Planform evolution including multiple cutoffs
Methodological approach	Modeling	Theoretical and mathematical modeling
	Laboratory	Experiments conducted in laboratory flumes or basins
	In-situ	Based on measurements taken in the field
	Remote sensing	Based on the information derived from remotely-sensed images (e.g., aerial photography, satellite images, LiDAR-derived data, etc.)
Conceptual approach	Reductionist	An approach that explains the processes and forms of natural systems (e.g., meandering channels) in terms of the laws of physics
	Holistic	An approach that advocates the idea that a natural system (e.g., meandering channels) and the properties of the system, should be viewed as wholes, not as sum of the components of the system because natural systems function as wholes, therefore, the functioning of natural systems cannot be fully understood solely in terms of the components.

Meandering patterns similar to those of rivers are also observed in depositional submarine fans at or beyond the base of the continental slope formed by turbidity currents (Flood and Damuth, 1987; Abreu et al., 2003) and on other planetary environments (Weihaupt, 1974; Bray et al., 2007; Howard, 2009). Meandering channels in submarine and extraterrestrial environments drew the attention of the scientific community later than the terrestrial counterparts (Shepard, 1966; Weihaupt, 1974). Growing interest in submarine meandering channels, since the beginning of 21th, century can be attributed mainly to the increasing availability of extensive high resolution data produced by new oceanographic bathymetric mapping technologies.

2. Why a special issue on meandering channels?

By the latter part of the 20th century, research on meandering rivers had increased to the extent that in 1983 the conference *Rivers'83*, sponsored by the American Society of Civil Engineers (ASCE), focused exclusively on such rivers. The symposium provided a forum for discussion and exchange of knowledge and ideas on the mechanisms and response of river meandering as well as the impact of human activities on meandering rivers. The widespread participation in the symposium by researchers from geology, engineering, and geography disciplines resulted in papers covering four broad discipline areas: geomorphology (32 papers), human impact (17 papers), engineering analysis of flow and sediment processes (23 papers), and numerical and physical modeling (17 papers), all of which were published in the well-known volume *River Meandering* (Elliot, 1984). The conference *Rivers'83* paved the way for the bilateral project "Development and Applications of the Theory of River Meandering" initiated by S. Ikeda and G. Parker and supported by U.S. National Science Foundation and the Japan Society for the Promotion of Science. The project involved three workshops attended by a group of theoretical and field-oriented researchers (eight civil engineers, three geologists, and a geographer) from USA, Japan, and Europe. The main purpose of these workshops was to develop a more unified understanding of the mechanics of river meandering by drawing together various perspectives. The workshops gave rise to a second set of papers on cutting-edge research published in the American Geophysical Union (AGU) Water Resources Monograph: "River Meandering" (Ikeda and Parker, 1989). This monograph had a catalytic impact on the field by synergizing the work of other researchers and stimulating further interest in the subject with a subsequent amplification of research on river meandering.

Advances in research on river meandering through the '90s and the beginning of the 21th century have focused specifically on several topics: *field-based or empirical* research on the interactions between flow structure and bed morphology (e.g., Lawler et al., 1997; Frothingham and Rhoads, 2003; Harrison et al., 2011) and on channel planform evolution (e.g., Hooke, 1995; Gilvear et al., 2000; Hooke, 2007; Luchi et al., 2007; Hooke, 2008; Güneralp and Rhoads, 2009b, 2010); *experimental- or laboratory-based* research on flow and sediment transport in curved channels (e.g., Whiting and Dietrich, 1993a, 1993b, 1993c; Blanckaert and de Vriend, 2004; Blanckaert and de Vriend, 2005; Peakall et al., 2007a, 2007b; Abad and García, 2009a, b; Braudrick et al., 2009; Termini, 2009) and *theoretical and numerical modeling* of meander morphodynamics (e.g., Odgaard, 1989; Tubino and Seminara, 1990; Furbish, 1991; Howard, 1992; Seminara and Tubino, 1992; Sun et al., 1996; Darby et al., 2002; Lancaster and Bras, 2002; Blanckaert and de Vriend, 2003; Bolla Pittaluga et al., 2009; Crosato, 2009; Dulal et al., 2010; Luchi et al., 2010; Güneralp and Rhoads, 2011; Luchi et al., 2011). The same period has also seen the development of research on submarine meandering channels focusing on the detailed characterization of meander geometry, migration rates, and interchannel-sedimentation patterns (e.g., Keevil et al., 2006; Peakall et al., 2007a; Dykstra and Kneller, 2009; Amos et al., 2010; Babonneau et al., 2010; Parsons et al., 2010), often building on approaches used to study meandering rivers.