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Advances and challenges in meandering channels research

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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

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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.

Over 20 years has passed since the last thematic publication on meandering rivers appeared. The fast pace of research developments on this topic provided an opportunity to bring together interested scientists to share new achievements, debate controversial issues and to set the stage for future research. Following informal discussions at various international- and national-level conferences, sessions focusing on meandering channels were held at the two major geosciences meetings in Europe and in the United States, namely the European Geosciences Union (EGU) Congress in 2008 and the American Geophysical Union (AGU) Fall Meeting in 2009. The session on "River meandering dynamics" held at the 2008 EGU Congress led to a special issue of *Earth Surface Processes and Landforms* entitled "River Meander Dynamics: Developments in Modeling and Empirical Analysis" (Hooke et al., 2011). The session and the special issue succeeded in bringing together researchers from many diverse disciplines, thereby highlighting various approaches to the study of meandering rivers, including mathematical and theoretical modeling (five papers), experimental research (one paper), and field-based empirical analysis (four papers).

The special session "Meandering Rivers: Advances in Research" at the 2009 AGU Fall Meeting also attracted considerable interest with a total of 30 paper and poster contributions. Similar to the previous meetings, this session served as a platform for discussion of advances and challenges in the field by bringing together researchers from civil and environmental engineering, geography, geosciences/earth and environmental sciences, along with representatives of various federal agencies and national labs (i.e., the U. S. Geological Survey and the U.S. Department of Agriculture, and Los Alamos National Laboratory). Besides emphasizing the importance of connecting field-based studies of meandering rivers with experimental studies and theoretical, mathematical modeling, this meeting also highlighted research on meandering channels in submarine and extraterrestrial environments. This special issue "Meandering Channels" has been produced in response to the high level of interest in the 2009 AGU session. It addresses the need for sustained scientific dialogue on the dynamics of meandering channels.

3. Overview of the contributions

This special issue consists of nine papers — eight research contributions and one opinion piece (Table 2). Most of these papers (eight of nine) examine meandering rivers, whereas the remaining research paper focuses on submarine meandering channels. The main focus of the fluvial papers is on interactions between flow and bed topography or between flow and bank erosion. The spatial scale ranges from channel-width scale to the reach scale and the temporal scale ranges from equilibrium scale to engineering scale (Table 2). The opinion paper addresses reductionist versus holistic approaches to the study of meandering dynamics — two prevailing (and sometimes competing) conceptual approaches (Seminara and Bolla Pittaluga, 2012–this issue). We organize the summaries of the contributions around the environmental domains (i.e., terrestrial versus submarine channels) and conclude with an overview of the opinion paper.

3.1. Meandering river channels

3.1.1. Modeling approaches

Motta et al. (2012–this issue) develop an integrated meander-migration model that relates the planform evolution of meander bends to stream-bank erosion processes and to the hydro-morphodynamics of the central flow region. This integration is achieved by coupling a first-order linear meander-morphodynamics model ("RVR Meander," (Abad and García, 2006), based on Ikeda et al., 1981) with a physically-based model based on the algorithms of CONCEPTS (*CON*servational *C*hannel *E*volution and *P*ollutant *T*ransport *S*ystem) (Langendoen and Alonso, 2008; Langendoen and Simon, 2008; Langendoen et al., 2009). The approach overcomes the limitation of most extant models of river meandering, which are based on the assumption that the rate of bank-erosion is linearly related to the excess near-bank velocity (Ikeda et al., 1981; Hasegawa, 1989). Rates of migration are related to the physical processes controlling bank retreat, such as hydraulic erosion and mass failure. The model also accounts for a natural bank profile and different soil layers in the profile. Several differences exist in predicted meander planforms using the traditional linear approach and Motta et al. physically-based model, namely in relation to bend skewness, sharp necks, and preferential migration of some bends. These resulting features are the outcome of the interplay between the channel hydrodynamics – represented by the streamwise varying near-bank shear stress – and the spatial variation of bank properties – expressed through the critical bank shear stress and the erosion-rate coefficient. Model predictions are in good agreement with observed migration patterns of a natural meandering stream (Mackinaw River, Illinois, USA).

Posner and Duan (2012–this issue) compare two different approaches of modeling the evolution of meander planforms: 1) using a constant, deterministic lateral migration coefficient, sometimes referred to as "bank erosion coefficient" (Ikeda et al., 1981; Hasegawa, 1989); and 2) using a spatially-uniform coefficient with a random variability and a probability density function satisfying either a normal or a uniform distribution. The near-bank flow field is obtained from the linear models of Ikeda et al. (1981) and Johannesson and Parker (1989). The random variability in the bank-erosion coefficient is assumed to account for the uncertainty associated with bank shear stress, soil composition, vegetation density and flow turbulence. Monte Carlo simulation is performed for the stochastic bank-erosion model. The channel-centerline evolution of a meandering channel is simulated with the same initial conditions of Friedkin (1945) laboratory experiments. The predictive capability of deterministic and stochastic models is assessed by quantifying the positional error in the simulated channel centerlines compared to the centerlines observed from the laboratory experiments. The centerlines obtained from the

Table 2
Contributions to the Special Issue: Meandering Channels.

Article	Environmental domain	Study focus	Space scale	Time scale	Methodological approach	Conceptual approach
Motta et al.	Terrestrial	Bank	Bend, reach	Engineering	Modeling	Reductionist
Chen and Tang	Terrestrial	Flow–bed	Bend	Engineering	Modeling	Reductionist
Posner and Duan	Terrestrial	Bank	Bend	Engineering	Modeling	Reductionist
Nardi et al.	Terrestrial	Bank	Width	Event	Laboratory	Reductionist
Ottevanger et al.	Terrestrial	Flow–bed	Bend	Equilibrium	Modeling	Reductionist
Engel and Rhoads	Terrestrial	Flow–bed, bank	Bend	Engineering	In-situ	Reductionist
Riley and Rhoads	Terrestrial	Flow–bed	Bend	Event	In-situ	Reductionist
Darby and Peakall	Submarine	Flow–bed	Bend	Equilibrium	Modeling	Reductionist
Seminara and Bolla Pittaluga	–	Opinion	–	–	Dialogue	Reductionist & Holistic

For the description of each category, refer to Table 1.

deterministic models of Ikeda et al. (1981) and Johannesson and Parker (1989) have errors of more than 50%, which are attributed to the high dependency on the calibration of the lateral migration coefficient. On the other hand, overall results from the stochastic version of Ikeda et al. (1981) model show that the centerline averaged over the Monte Carlo simulations provide a more accurate representation of the observed centerline.

Chen and Tang (2012–this issue) evaluate the role of topography- and curvature-driven secondary flows on the evolution of sine-generated meandering channels. The approach employs an analytical flow-field solution and a physically-based bank-erosion model to determine channel migration. The hydrodynamic solution is obtained from 2-D, depth-averaged, quasi-stationary flow equations in channel-fitted orthogonal coordinates. The solution has a constant channel width assumption that is valid only for quasi sine-generated channels (Johannesson and Parker, 1989). Bank erosion is modeled using the Bank Erosion and Retreat Model (BERM). BERM assumes that the rate of bank erosion equals the rate of retreat of the top of bank and computes the rate of erosion as a function of the flow field, sediment transport, properties of bank material, and bank geometry (i.e., slope) (Chen and Duan, 2008). Using this flow–bank erosion model, Chen and Tang conduct numerical experiments with input parameters obtained from two laboratory studies of meandering channels. They evaluate the sensitivity of channel evolution to scour factor (A), defined as a function of lateral bed slope and channel curvature, and secondary-flow effects (A_s), introduced by Johannesson and Parker (1989) (pg. 1029, Eq. (36)). A and A_s represent the momentum redistribution exerted by topography- and curvature-driven secondary currents, respectively. In contrast to previous studies, A, in this study, is assumed to increase with increasing channel curvature (i.e., with increasing depth-averaged streamwise velocity) and, therefore, change with time (Zimmerman and Kennedy, 1978; Ikeda et al., 1981; Odgaard, 1989). Similarly, A_s is also assumed to increase as the channel evolves by increasing its planform sinuosity. Following the work by Chen and Duan (2006), Chen and Tang also examine a series of scour-factor functions varying in time. The results show that the evolution of sine-generated meandering channels is sensitive to secondary flow. The presence of secondary flow leads to a more sinuous pattern with more lateral extension compared to the case without secondary flow. Moreover, the role of secondary flow is less significant in meander evolution compared to that of primary flow. Treating scour factor A as a time-varying parameter provides more realistic patterns of meander evolution than treating it as a constant.

Ottevanger et al. (2012–this issue) examine the redistribution of dominant velocity and nonlinear interaction processes in sharply-curved, short meander bends with significant variations in planform curvature. The analysis is based on the reduced-order nonlinear model of Blanckaert and de Vriend (2003, 2010). The model is valid for mildly- and sharply-curved bends in contrast to linear (Camporeale et al., 2007) and weakly-nonlinear models (Seminara and Tubino, 1992; Bolla Pittaluga et al., 2009), which are strictly valid only for mildly-curved bends. The model accounts for the influence of 1) topographic steering, 2) high variations in curvature, and 3) secondary flows on the velocity distribution in bends. Flow-velocity distributions observed in one laboratory and two meandering river channels are simulated: 1) Kinoshita flume, a narrow laboratory flume with rectangular cross-section and smooth boundaries (Abad and García, 2009a; 2) a very narrow natural bend characterized by nearly-flat bed topography and the quasi-absence of secondary flow (Nanson, 2010; 3) a sharp natural bend, with gradually varying channel width, marked horizontal recirculation zones, and the patches of vegetation at the river bed. The results quantify the major differences between hydrodynamic processes governing sharply- and mildly-curved bends. The relative importance of the factors governing flow redistribution depends on reach-scale characteristics (i.e., roughness and shallowness) and bend-scale characteristics (i.e., bend curvature and the extent of variations in planform curvature) of the meandering channel. In sharply-curved bends, the effect of variations in curvature is significant but it is negligible in mildly-curved bends — a finding supported by recent work on planform curvature–migration relations in natural meandering rivers (Güneralp and Rhoads, 2009a, 2010). The results also show that nonlinear hydrodynamic interactions, accounted for by the model, decrease the growth of secondary flow with increasing curvature, thereby, leading to a reduction in the transverse bed slope and in the effect of topographic steering. The findings are significant for improving the predictions of redistribution of velocity and strength of secondary flow, and thus, of meander migration in meandering channels with sharply-curved bends.

3.1.2. Laboratory-based approaches

Nardi et al. (2012–this issue) conduct a set of physical laboratory experiments to determine the processes and critical factors governing bank retreat in coarse-grained riverbanks. Current models of erosion of coarse-grained layers at the bank toe are based on geotechnical models of slope failure. These models assume an ultimate stable angle equal to the angle of repose and cannot reproduce commonly observed near-vertical riverbanks composed of coarse sediment. Thus, Nardi et al. develop a physical laboratory model, which replicates the coarse-grained basal layer of a riverbank profile. The physical model is based on the bank characteristics of a dynamic real river. The riverbanks are composed of a basal layer of packed and slightly-cemented gravel located at the bank toe and fine-grained cohesive material at the upper portion of the banks. Nardi et al. conduct experiments with the physical model to examine the roles of cohesion in the fine-sediment matrix, packing, partial cementation of the material, and vegetation. In the experiments, they also consider a range of slopes (i.e., 75°–90°), degree of cementation, and the oscillation of water level that causes variations in pore water pressures. The results demonstrate that the processes governing erosion and failure in riverbanks composed of coarse-grained material are significantly different than those in riverbanks composed of fine-grained material. Loss of matric suction is the primary process governing riverbank erosion and failure. In riverbanks composed of materials with high degrees of cementation, other important factors governing bank erosion and failure include the presence of positive pore pressure, increase in sediment unit weight, and infiltration along boundaries of layers with different material composition. Moreover, the period corresponding to the rising limb of a hydrograph is critical for the occurrence of mass failures because of basal scour. These findings can help better characterize the process of bank retreat in coarse-grained riverbanks. This knowledge can then be incorporated into the morphodynamic models of meandering channels with the aim of improving our understanding of the dynamics governing the processes of planform evolution.

3.1.3. Field-based approaches

Building upon work by Frothingham and Rhoads (2003), Engel and Rhoads (2012–this issue) present a long-awaited study to explain process interactions among turbulent flow structure, bank failures, bed morphology, and channel planform in a meander bend over the timescale of planform change. The meander bend is a highly-dynamic compound loop with well-developed pool-riffle sequences and point bars. Engel and Rhoads examine annual repeat surveys of channel morphology over a period of 11 years and three-dimensional (3-D) flow-velocity obtained at the beginning and end of this period. Their findings indicate that patterns of bank erosion are controlled by near-bank flow turbulence, which are strongly influenced by local factors, such as the deflection of flow by point bars (i.e., topographic steering) and preserved blocks of failed bank material. These local factors can either inhibit or enhance the development of strong velocity gradients and high values of turbulent kinetic energy, and, thus, erosion at the bank toe. Thus, spatial patterns of near-bank velocity and turbulence may not entirely correspond to the patterns of planform curvature in contrast to this assumption in the mathematical models of meander morphodynamics. Moreover, the spatial patterns of mean flow and turbulence, observed in the meander at the beginning of the period, are consistent with the patterns of channel migration over the period. The study presents a unique field-based investigation of the spatial structure of the turbulence in the outer banks of meander bends and its relation to the patterns of planform change. It gives new insights to the feedbacks among relevant processes governing the dynamics of meandering rivers at different temporal scales as well as morphological responses to these processes at different spatial scales. The study advances our understanding of the linkages between meandering channel processes at various spatial and temporal scales, and, thus, should help improve current models of meander-morphodynamics.

Riley and Rhoads (2012–this issue) examine the flow structure and bed morphology at a natural confluent meander bend — an important, yet under-studied type of the configuration of a meandering river. Confluent meander bends are geomorphic landforms commonly observed in nature at the junctions of meandering channels with tributaries. The confluent meander examined in this paper is formed by a high-angle junction of an elongated meander loop and a tributary channel. The tributary channel enters the elongated meander at the outer bank near a local maximum of channel curvature on elongated loop. The observed flow structure and bed morphology, obtained from the field measurements on 3-D velocity components and topographic surveys, confirm that high-velocity flow and helical motion in the main channel are deflected toward the inner bank by the flow entering from the tributary meander. This deflection leads to bed scour near the inner bank and prevents point-bar development. The high-angle junction of the tributary and the main channel causes the tributary-flow direction to abruptly adjust to the spatial configuration of the main channel downstream of the junction, initiating a cell of helical motion along the outer portion of the bend that co-exists with a helical cell generated by curvature of flow moving around the bend. Riley and Rhoads also investigate the changes in flow structure and channel morphology of the study site between two hydrological events and compare the changes to the long-term planform stability of the confluent meander. The results show that an increase in momentum-flux ratio leads to increased penetration of tributary flow into the main channel flow, shifting the mixing interface toward the inner bank of the main channel. The results also reveal that channel morphology undergoes only minor changes even after experiencing high discharges and formative flows. This finding suggests that the configuration of confluent meander bend has long-term planform stability, and supports a previously proposed hypothesis about the quasi-stable nature of confluent meander bends (Parker, 1996).

3.2. Submarine meandering channels

Turbidity currents often form submarine meandering channels (Pirmez and Imran, 2003), which are in many ways analogous to terrestrial meanders. One of the key elements in the development of such an analogy is the direction of secondary flow with field and experimental evidence (e.g. (Amos et al., 2010; Parsons et al., 2010) as well as theoretical analyses (e.g. (Abad et al., 2011) indicating that submarine meandering channels can exhibit river-like and river-reversed secondary circulation. Darby and Peakall (2012–this issue) explore possible differences in bed morphologies between equivalent bends subjected to river-like and river-reversed secondary flows. This comparison is achieved by modifying the model of Bridge (1992) for flow and bed topography in meandering channels by replacing the logarithmic vertical profile of flow velocity with a vertical profile having its maximum close to the bed. Such a profile is more appropriate for turbidity currents and, under certain hydraulic conditions, forces secondary flow to exhibit the reverse sense with respect to that of fluvial bends. To test the model, predicted and observed bed profiles at the apices of meander bends shaped by turbidity currents are compared using field data for one active submarine channel bend in the Black Sea, seven inactive meander bends in the Gulf of Alaska, and three meander bends in laboratory experiments. Two main morphological implications of secondary flow reversal are suggested by the model. First the transverse bed slope for the river-reversed secondary flow is smaller than in river-like case, with shallow outer-bank pools and less-pronounced point bars. Second, the position of the depositional point bar is located farther downstream than where it is normally positioned in fluvial bends.

3.3. Conceptual approaches in meandering channels research

Seminara and Bolla Pittaluga (2012–this issue) discuss two prevailing conceptual approaches in meandering channels research through an interesting Socratic dialogue between two imaginary scientists: a *reductionist* who supports only the theories based on physical principles and is skeptical about new paradigms, and a *holistic* who supports new paradigms and tools to analyze a meandering river system as a whole in the context of its environment. These two imaginary scientists review popular issues in meandering rivers research by highlighting distinctive reductionist and holistic viewpoints throughout the dialogue. They start by discussing two important concepts, “uncertainty” and “qualitative” and ask the question “Can meandering rivers be considered complex systems?”, which sets the stage for further discussion. The main topic of discussion is whether chaotic response and self-organized criticality exist in meandering channel dynamics. To answer this question, they evaluate the evidence of nonlinearity in meandering dynamics and fractality in meandering channel patterns, both of which may result from the existence of chaotic dynamics.

Both scientists agree on the presence of nonlinearity in meandering channels in the real world, evidenced by the emergence of complex meander forms such as compound loops (i.e., generation of higher harmonics) from simple bends, and the presence of thresholds such as cutoffs that occur during meander evolution. The reductionist, however, advocates that the source of the nonlinearity is geometric. Based on the meander migration patterns obtained from mathematical models of meander evolution, the reductionist also advocates that the nonlinearity is weak before the occurrence of cutoffs. Moreover, the reductionist argues that cutoff processes and external forcing are not a further source of nonlinearity; instead, they prevent geometric nonlinearities from emerging fully in the long-term planform evolution (Perucca et al., 2005). Both scientists agree that fractal dimension is a useful morphometric variable for characterizing the complexity of planforms and reach a consensus on the fractal nature of meandering channel planforms.

Determining whether the dynamics of meandering channels have chaotic response is not an easy task. Based on the analysis performed using mathematical models, the reductionist argues that the sources of nonlinearity in meander evolution do not support the occurrence of chaotic response in meandering channels. Moreover, any significant divergence of nearby trajectories in the numerical simulations of meander evolution is not detected, as opposed to the case in chaotic phenomena where such divergence is expected (Frascati and Lanzoni, 2010). On the other hand, the mathematical models in which the conclusions of the reductionist are rooted do not take into account other potential sources of nonlinearity such as the nonlinearity in hydrodynamics and sediment transport. Nevertheless, whereas mathematical models have a limited ability to represent the real world, the results obtained from the empirical analysis of meandering can be misleading because of a range of factors that could bias the results, such as insufficient amount of data and heterogeneity in flow, sediment, and geology.

Final discussion is on a potential platform that can bring reductionist and holistic approaches together. A consensus is somewhat reached on the utility of cellular models (i.e., rule-based models) in studying the long-term morphodynamic evolution of a geomorphic system. Well-founded cellular models are then seen as an alternative to the equation-based fully-reductionist approaches. Cellular models represent an ideal system composed of cells whose interactions are defined by a set of rules. Explicit consideration of the interactions among the cells may lead to some emergent patterns as a response to the dynamics of the system. Notably, the main purpose of cellular model-based approaches is to develop an understanding of the response of the system over time and space, and of the interactions among its components, rather than performing predictions of the observed dynamics of the system.

4. Concluding remarks

Research on meandering channels, similar to the research on other fluvial systems, is a vast and dynamically changing field, spanning a broad variety of disciplines, environmental domains, time-space scales, and conceptual and methodological approaches. This introduction has attempted to frame the overall contributions of this special issue in the broad context of meandering channels research (Table 2). Within this context, this special issue can be considered as highly focused with most contributions addressing interactions between flow structure, bed morphology, and/or bank erosion processes. The spatial scale of the studies ranges from channel-width to reach scale and the time scale ranges from equilibrium to engineering scales. More than half of the contributions are based on mathematical modeling, two are based on in-situ field measurements, and one paper is based on laboratory experiments. One paper serves as an original and intriguing contribution to the debate between reductionist and holistic approaches to the study of meandering channels.

Each paper identifies future research needs in relation to its topical focus. To conclude, we define five broad future research directions suggested by an overall consideration of the set of contributions, guided by the scope of the research in meandering channels presented in Table 1. Three proposed directions reflect the dominance/absence of contributions on selected topics within this special issue; two additional directions deal with potential improvements to current conceptual and methodological approaches. The proposed directions are restricted to research on meandering rivers and do not address needs for channels in submarine or other planetary environments.

4.1. Coupling of near-bank geomorphic and flow processes

Meander morphodynamic models traditionally restrict the flow description to the central flow region and have simplified treatment of bank dynamics, with a strong bias towards that of the eroding (outer) bank, for which more detailed knowledge is available (Rinaldi and Darby, 2008) compared to the advancing (inner) bank. Several contributions in the special issue emphasize the importance of detailed understanding of near-bank flow processes (Engel and Rhoads, 2012–this issue) and accurate physical description of bank erosion mechanisms (Nardi et al., 2012–this issue) for improved prediction of planform change (Motta et al., 2012–this issue). Improvements in the characterization of flow and related morphodynamic consequences are being achieved for bends of sharp curvature (Ottevanger et al., 2012–this issue), for bank-erosion processes governing different types of sediment (e.g., fine-grained vs. coarse-grained bank material), and for banks with different types of profiles.

4.2. Improving the characterization of planform change through an integrated perspective: co-evolution of meandering rivers and the floodplains

Studies of planform change are common in meandering rivers research, but are not fully represented in this special issue (see Motta et al., 2012–this issue). The common approach to modeling of river meandering is to focus solely on the eroding bank (i.e., cutbank) and on the role of bank erosion processes in channel migration. This approach is based on the assumption that the accretion on the point bar keeps pace with the erosion of the cutbank, giving a constant channel width along the planform. Nevertheless, the accretion processes and the role of the accreting bar (i.e., point bar) are also important in the dynamics of channel migration (Engel and Rhoads, 2012–this issue). The governing processes of accretion are significantly different than the processes of erosion. The spatial and temporal patterns of accretion depend on inundation and vegetation-succession dynamics, both of which are controlled by the hydrologic and topographic characteristics of a particular river as well as by the interaction between the vegetation- and morphodynamics of the meandering river–floodplain system (i.e., bio-morphodynamics). Thus, for a process-based and predictive understanding of meander migration, the key processes governing the accretion dynamics should also be taken into account (Parker et al., 2011). In this respect, research on braided-channels has been much more progressive by taking into consideration cutbank and point-bar migration processes as well as channel evolution in the presence of vegetation (Bertoldi et al., 2011; Gurnell et al., 2012). Nonetheless, significant advancements are emerging in determining the effects of vegetation on the morphodynamics of meandering rivers (Perucca et al., 2006, 2007).

The success of the studies on the bio-morphodynamics of meandering river channel–floodplain system depends on developing a robust framework that can take into account spatial heterogeneity. In-depth systematic investigations of the role of floodplain heterogeneity and variability in riverbank profiles on the morphodynamic evolution of meandering channels are just beginning to emerge. A recent numerical study demonstrates the strong influence of the scale and the magnitude of floodplain erosional heterogeneity on patterns of planform evolution (Güneralp and Rhoads, 2011). Further empirical work is needed to examine in detail how specific types of floodplain heterogeneity (e.g. sedimentary, biotic, topographic, geologic, land use) affect planform evolution. Also, integration of these effects into planform evolution models is vital for advancing our process-based understanding of these dynamic interactions and for developing improved forecasts, management and restoration practices of meandering river–floodplain systems.

4.3. Improved linkage between research on meandering-rivers and river management and restoration

This special issue does not include studies explicitly focusing on the management and restoration of meandering rivers. Given the ongoing efforts to restore regulated streams in Europe and North America, many re-meandered streams can be used as ideal field sites to study the processes of meandering. Moreover, knowledge gained through the post-monitoring of the sites that are managed with different management strategies can strongly help improve the theoretical and decision-support tools on which those choices have been made (Kondolf, 2006). Furthermore, the substantial body of knowledge on the dynamics of meandering rivers has, thus far, not been fully exploited, particularly for prediction and assessment of habitat quality (Beighley et al., 2009; Hauer et al., 2011). Improvements in linkages between the knowledge gained from recent research on meandering rivers and river management and restoration practices will contribute to effective solutions to restoration and management problems as well as provide better assessment and prediction of habitat-quality.

4.4. Expanding the research employing laboratory-based approaches

Laboratory experiments can significantly contribute to a deeper understanding of the feedbacks between channel morphodynamics and floodplain vegetation and morphodynamics. Two recent laboratory-based studies, one focusing on the conditions necessary to sustain meandering in coarse-bedded rivers (Braudrick et al., 2009) and the other one on the influence of vegetation on channel morphodynamics

(Tal and Paola, 2010), exemplify the great potential that laboratory-based research can provide for understanding the co-evolution of meandering river–floodplain systems. As is apparent from the findings of these studies, a need exists for laboratory experiments that include moveable bed and erodible bank conditions to address the co-evolution of river–floodplain systems, contrary to the classical experimental approaches where bank and/or bed conditions are commonly fixed. Future laboratory models should also characterize spatial heterogeneity in floodplain conditions as well as the temporal variability in discharge conditions (e.g., Visconti et al., 2010). Integration of such detailed processes into laboratory models also creates new challenges associated with appropriate scaling and experimental design.

4.5. Integration of holistic and reductionist approaches

The opinion paper presents the two major, but significantly different conceptual approaches that are commonly employed in research on meandering channels. The discussion presented in the paper is valuable in the context of meandering channels research and provides insight into current perspectives on and future directions in geomorphology in general. As also acknowledged by Seminara and Bolla Pittaluga (2012–this issue), great potential exists for a new generation of hybrid reductionist–holistic models of planform evolution. One of the earliest examples of these hybrid models applied to meandering channels is the cellular model of Coulthard and Van De Wiel (2006), which integrates meandering processes with a landscape evolution model using a cellular automation framework. Hybrid models will facilitate examination of the emergence of spatial patterns resulting from the co-evolution of meandering river–floodplain systems as well as the influence of environmental factors, such as climate change and human impacts, on the emergence of these spatial patterns (Van De Wiel et al., 2007). Moreover, hybrid models will provide exploratory platforms for examining the emergence of deterministic chaos from the physical processes governing the response of the system.

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