Modern empirical and modelling study approaches in fluvial geomorphology to elucidate sub-bend-scale meander dynamics

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ABSTRACT. Major developments in theory and modelling techniques have taken place within the past couple of decades in the field of the fluvial geomorphology. In this review we examine the state-of-the-art empirical and modelling approaches and discuss their potential benefits and shortcomings in deepening understanding of the sub-bend-scale fluvial geomorphology of meander bends. Meandering rivers represent very complex 3D flow and sedimentary processes. We focus on high-resolution techniques, which have improved the spatial and temporal resolution of the data and thereby enabled investigation of processes, which have been thus far beyond the capacity of the measurement techniques. This review covers the measurement techniques applied in the field and in laboratory circumstances as well as the close-range remote sensing techniques and computational approaches. We discuss the key research questions in fluvial geomorphology of meander bends and demonstrate how the contemporary approaches have been and could be applied to solve these questions.

Key words
Fluvial geomorphology, Laser scanning, ADCP, photogrammetry, hydraulic modelling, meandering

I Introduction

Meandering rivers with sinuous planforms (one of the most common river planform types) are characterized by unevenly distributed flows and sediment transport patterns (Fig. 1). The lateral changes in their courses can be rapid or even dramatic due to migration and cut-offs. The fundamental theories of meander evolution and conceptual models describing the sub-bend-scale processes, such as the flow and sediment transport patterns within a meander bend, were established during the latter half of the 20th century, and the basic principles of these theories have remained unchanged since then. The increased availability of computational power during the late 20th and early 21st centuries, however, has led to rapid progress in empirical measurement and computational modelling techniques. This has enabled riverine investigations with higher spatial and temporal resolution than were possible before, leading to inspections of phenomena that had earlier been beyond researchers' measurement and modelling capacities. This has also led to a resurgence of studies dealing with meandering river processes. Many field studies (e.g. Engel and Rhoads, 2012;

Ferguson et al., 2003; Frothingham and Rhoads, 2003; Gautier et al., 2010; Hooke, 2008; Hooke and Yorke, 2010; Milan et al., 2007) and modelling-based studies (e.g. Ferguson et al., 2003; Güneralp and Marston, 2012; Kasvi et al., 2013b, 2015b; Kleinhans, 2010) have been published recently with the intent of gaining a more profound understanding of meandering channels' somewhat predictable but complex processes and changes.

Many processes and phenomena, mainly those related to the 3-dimensionality found in meandering rivers, are still beyond measurement capacity and thus can only be approached implicitly. Computational models, which are always simplifications of the real world, also have their deficiencies. For instance, sub-grid-scale processes, such as turbulence, cannot be modelled and thus have to be parameterised. Sediment sorting and transport are great challenges for computational modelling in the second decade of the 21st century. Therefore, in fluvial geomorphology, combining various study approaches (i.e., empirical observations and modelling) has become increasingly popular, as each approach represents nature in a different way and the deficiencies of one approach can be compensated for by using others (e.g. Casas et al., 2010; Darby et al., 2002; Güneralp and Marston, 2012; Kleinhans, 2010; Lane et al., 2007; Lotsari et al., 2014a; Ottevanger et al., 2012). The increased spatial and temporal resolution achieved by combining conventional field measurements with a range of modern technologies enables researchers to provide new insights into meandering river processes and their spatial and temporal patterns; this improved resolution has already been exploited to some degree. However many of the possibilities from the combined study approaches have not been fully exploited, and much remains to be done.

Güneralp and Marston (2012) published a detailed review of meandering river research, giving much attention to descriptions of the studies' theoretical modelling approaches, which ranged from simple kinematic models to more advanced fluid dynamics, including bank erosion and sediment transport models using evolving bed topography. Theynoted the need for bridging the gap between theoretical modelling and field- and laboratory-based research for practical river management purposes, such as assessments of river hazard risks and practices for river management and restoration. However, they did not focus on the current state of understanding regarding the sub-bend-scale processes of meander bends. They also did not introduce or assess modern empirical measurement techniques, which have recently opened up many research opportunities for fluvial geomorphologists. Hooke (2013) provided a comprehensive review of the meandering river research. She introduced the phases of the meander research, the various study approaches, their achievements, and the remaining challenges in the field of meander studies. She also gave a detailed description of the recent studies regarding long-term meander evolution at reach scale. She pointed out that, despite recent achievements in empirical studies, more field-based research is needed. However, she did not review the state-of-the-art methods, which have enabled a focus on sub-bend-scale processes with increased detail and reliability. Neither did she discuss the recent thematic achievements concerning meandering river processes that this methodological development has enabled.

Thereby, the aim of this paper is to complete these recent comprehensive reviews by focusing on the potential benefits and shortcomings of the modern empirical and modelling approaches in deepening understanding of the sub-bend-scale fluvial geomorphology of meander bends. Our study is focused on key research questions concerning sub-bend scale processes in meandering rivers, which still remain partly unexplained but to which recent studies have given new insights: (1) What controlling factors interact during meander development and how are they interconnected? (2) Are the sub-bend-scale processes of the bends predictable or consistent?

Fig. 1a) A meandering river consisting of sequential bends with steep outer banks and shallow inner banks. b) The shallow and wide point bar on the inner bank.

We provide a brief overview of the history of the meandering river research, including the widely accepted general theories regarding the flow and sedimentary patterns of meander bends. After that we introduce the empirical and modelling approaches while focusing on the state-of-the-art methods, their advantages, disadvantages and possibilities in sub-bend scale studies. We discuss the key research questions and demonstrate how the contemporary approaches have been and could be applied to solve these questions: first we discuss the advances in fluvial, and then in morphodynamic processes research. We conclude with a general overview of the current status of the research and suggestions for future directions.

II History of meandering river studies

The early contributions in the study of fluvial geomorphology of meandering rivers date back to the 20th century, when the first hypothesis and theories were outlined, based on observations of landforms and processes, physical experiments, and aerial photographs, (e.g. Davis, 1902; Friedkin, 1945; Inglis, 1937; Jefferson, 1902). These pioneering studies were followed by a period of quantitative research between the 1950s and 1970s, when researchers were eager to discover the statistical and process-form linkages present in meandering rivers (e.g. Ackers and Charlton, 1970; Leopold and Langbein, 1966; Leopold and Wolman, 1957; Schumm and Khan, 1972).

During the 1970s, a considerable number of field-based empirical studies provided new insights into meandering rivers. Those studies indicated that, rather than reaching an equilibrium, as had been claimed earlier (e.g. Ackers and Charlton, 1970; Leopold and Langbein, 1966), the meanders were actually developing continuously (Brice 1974; Lewin, 1972, 1976; Hickin, 1974; Hickin and Nanson, 1975; Hooke, 1984). Several important studies in this era were also grounded in direct field measurements of sub-bend scale processes. The increasingly detailed observations allowed investigation of the complex patterns of fluvial and morphological processes within the bends (e.g. Bathurst et al., 1979; Bluck, 1982; Bridge and Jarvis, 1976; Dietrich et al., 1979; Hooke and Harvey, 1983; Dietrich and Smith, 1983, 1984; Thompson, 1986; Thorne et al., 1985). Concurrently, flume studies provided new insights into the sub-bend-scale processes (e.g. Hooke, 1975). Based on those studies, the conceptual models of meander bend processes were developed; these models have not been notably updated.

According to the conceptual models of meander evolution established in that era, which are still considered valid, the meander bends in different phases of development are classified into four groups: simple symmetric, simple asymmetric, compound symmetric and compound asymmetric (Brice, 1974). The sub-bend-scale processes (such as erosion at the point-bar head or convex bank beyond the apex and deposition over the point-bar tail) are key factors in the meander evolution leading the bend from one phase to another. In a simple symmetric bend, this leads to a gradual increase in the meander amplitude and sinuosity, and the point bar grows laterally towards the outer bank (Brice, 1974; Hickin, 1974; Hooke, 1977). The outer bank's erosion occurs further upstream, and the asymmetry of the bends increases, forming a compound bend and continuing to a cut-off – a sudden decrease in curvature (Hickin, 1974; Hooke, 1995). After the cut-off, the development starts from the beginning.

Much was achieved during the 1970s and 1980s with respect to the fundamental theories of the sub-bend-scale meandering behaviour, and the subject was considered rather mature; thus, this period was followed by a relatively quiet era in field-based meandering research, with few exceptions (Hooke 1995a, 1995b, 1997; Ikeda and Parker, 1989). However, in the wake of new technological developments, the first theoretical models performing a continuous meander development were formulated, which further strengthened the scientific community's consensus that meanders do not exhibit an equilibrium state (Bridge, 1992; Ikeda and Parker, 1989; Mosselman, 1995). Concurrently, due to the increased availability of computational power, the approaches based on computational fluid dynamics (CFD) became increasingly popular among fluvial geomorphologists (e.g. Hodskinson, 1996; Lane et al., 1996, 1999; Nicholas, 2001). Mathematical models have since been increasingly used in the assessment and development of theories regarding meandering behaviour, creating challenges for the field and laboratory experiments investigating natural processes (e.g. Booker et al. 2001; Crosato, 2009; Crosato and Mosselman, 2009; Ferguson et al., 2003).

The development of new empirical measurement techniques (such as close-range remote sensing and acoustic techniques) in the late 20th and early 21st centuries allowed for measurements of processes and phenomena that had been beyond the measurement capacities of the traditional techniques. Thereby, during the 21st century, an increasing number of empirical, theoretical and CFD-based studies have been published with the aim of deepening understanding of meander dynamics. Even though many details are still not completely understood, the methodological achievements have provided valuable new insights into these complex processes.

III Traditional understanding of flow and sedimentary patterns, and forms in meander bends

In meandering rivers, bends with different amplitudes and radii of curvature form a continuous sinuous channel (Fig 2). A meander bend usually consists of a gentle point bar attached to the convex side and a deep pool on the steep, concave side (Friedkin, 1945; Leopold and Wolman, 1960). Meandering is initiated as a result of complex interaction between flow, bed sediment, bank material, relief and vegetation. Disturbed flow in straight channel starts oscillating, forming alternate bars which cause shoaling and divergence of flow. This enables further bank erosion and bar growth and initiation of curvature along the channel (Ackers and Charlton, 1970; Schumm and Khan, 1972). The curved shape of the channel maintains the spatial variation in the flow and sedimentary processes along the bends.

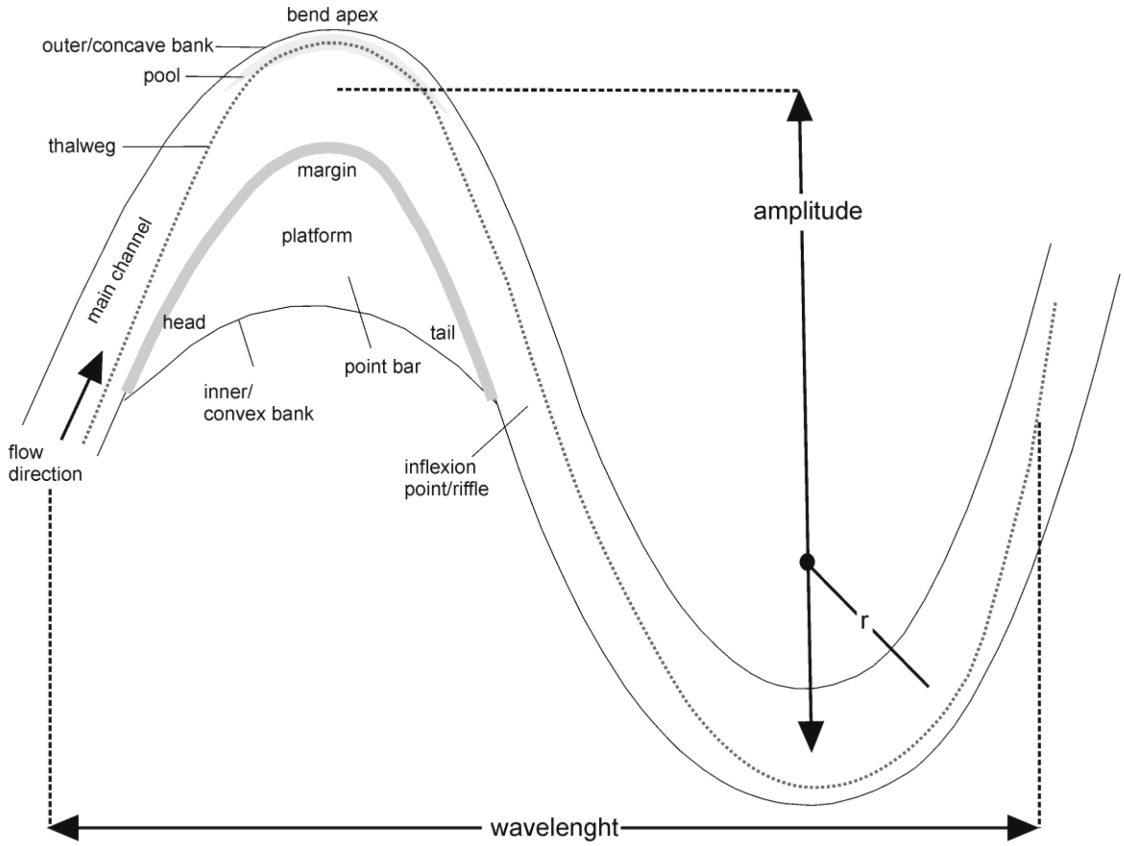

Fig. 2. Meander bend: terminology and parameters. The planform of the figure consists of two bends. The head, tail, platform and margin are parts of the point bar and are marked in the left bend. The letter r stands for radius of curvature. After Kasvi (2015).

When the flow enters a meander bend, the high-velocity core (HVC) is situated near the inner bank, shifting gradually towards the outer bank along the bend due to the shoaling of the flow over the point bar and the bend curvature (Bridge and Jarvis, 1976; Dietrich et al., 1979; Dietrich and Smith, 1983, 1984; Hooke, 1975). The outward flow causes a superelevation at the concave (outer) bank, which enforces a downwards flow along the outer bank and continues as an inwards near-bed flow and an upwards flow at the inner bank (e.g. Bathurst et al., 1979; Bridge and Jarvis, 1982; Dietrich and Smith, 1983). This circulating cell is called a secondary circulation of flow (Fig. 3). The outward flow may, however, dominate the entire water column at the upstream part of the point bar, thus limiting the secondary circulation to the pool and the downstream part of the point bar (Dietrich and Smith, 1983). Furthermore, at bends with steep outer banks, small cells of reverse rotation may appear near the outer banks (e.g. Bathurst et al., 1979; Thorne et al., 1985). The strength of the secondary circulation increases proportionally to the relative curvature and discharge (e.g. Bathurst et al., 1979; Engelund, 1974). With a very high discharge, however, it diminishes or saturates (Bathurst et al., 1979).

Due to the transverse shift of the HVC towards the outer bank, the maximum stream power and sediment flux shifts from the inner bank towards the outer bank as the distance downstream increases. The outwards flow throughout the water column at the upstream part of the bend and over the point-bar head, combined with the gravitational force forcing large particles towards the pool, intensifies the outwardly directed sediment transport (Dietrich and Smith, 1984). The low-flow velocities control the bar tail and, accompanied by a recirculation zone at the point-bar margin beyond the apex, lead to the deposition of fine material over the point-bar tail (Bridge and Jarvis, 1976).

During very high discharges, the flow can straighten its way across the point-bar platform as a chute current, eroding a chute channel at the inner bank, with chute bars and coarse grain sizes over the point-bar head and chute (e.g. Bridge and Jarvis, 1976; Dietrich and Smith, 1984; McGowen and Garner, 1970). At lower discharges, the HVC is located closer to the outer bank (at the bend entrance) and shifts towards the outer bank at a point further upstream than it would in a high discharge (Hooke, 1975). Thereby, during low discharges, the current over the bar head remains weak and even diminishes, which enables small particles from further upstream to fill the point-bar margin (McGowen and Garner, 1970). These flow and sedimentary patterns keep the meandering rivers in a continuous state of development.

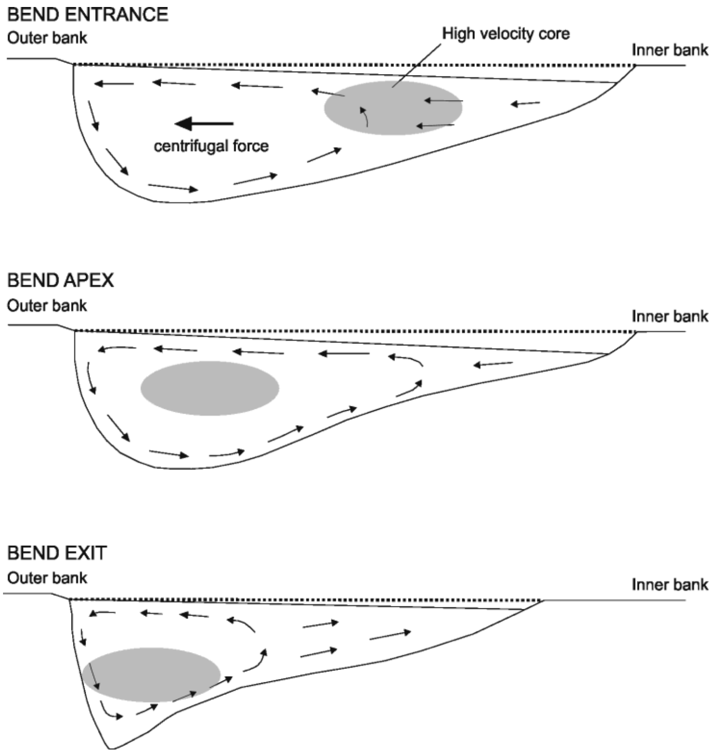

Fig. 3. A simplified model of the flow structure over a meander bend. The three cross-sections represent different parts of the bends: upstream, middle and downstream. The grey ellipse represents the high-velocity core, and the arrows illustrate the direction of the secondary flow (After Kasvi, 2015)

IV Contemporary study approaches in fluvial geomorphology

The flow field and channel in meandering rivers are in continuous states of change. Three-dimensional flow fields induce unevenly distributed sediment transport patterns, which in turn causes spatial variations in the morphological changes. The flow field reflects the bed topography. Therefore, one of the main challenges in empirical surveys of meandering rivers has been to achieve sufficient spatial and temporal resolution to study the rapidly evolving fluvial processes and forms with the required level of detail (Heritage and Hetherington, 2007; Knighton, 1998) (Table 1). On the other hand, computational modelling faces different challenges (Table 1).

Table 1. Modern empirical and modelling approaches used in fluvial geomorphology and their strengths and limitations.

Method	Measurement targets	Pros and cons	Studies applying
TLS	Topography,	(+) Very high measurement accuracy	Brasington et al., 2012;
	bed forms,	(+) Rapid compared to traditional methods	Heritage and Milan, 2009;
	grain sizes,	(-) Rather labourous	Hodge et al., 2009; Kasvi et al., 2013;
	channel change	(-) An accessible, flat scanning platform required	Milan et al., 2007; Morche, 2008;
		(-) Requires special expertise to perform	Pizzuto et al., 2010
		(-) Expensive	
MLS	Topography,	(+) High positional accuracy, efficient	Alho et al., 2009a; Kasvi et al., 2013;
	bedforms,	(-) Requires special expertise to perform	Kukko et al., 2007; Lotsari et al., 2014;
	channel change	(-) No factory-made products available yet	Vaaja et al., 2013; Wang et al., 2013
		(-) Expensive	
SfM	Topography,	(+) Rapid and relatively simple	Fonstad et al., 2013;
PHOTOGRAMMETRY	bedforms,	(+) Enables high spatial resolution	Javernick et al., 2014;
	channel change	(-) Spatial resolution not comparabe to TLS and MLS	Micheletti et al., 2014;
		(-) Requires special expertise to perform	Micheletti et al., 2015;
		(-) Requires special expertise to perform	Westoby et al., 2012
TERRESTRIAL	Topography,	(+) Relatively cheap	Brasington et al., 2003a;
PHOTOGRAMMETRY	channel chnage	(+) Enables surveys of vertical banks	Barker et al., 1997b; Chandler et al., 2005;
		(-) An accessible, flat scanning platform required	Lane et al., 2001;
		(-) Requires special expertise to perform	Westoby et al., 2012
AIRBORNE	Topography,	(+) Especially good in defining evolving channel boundaries	Hooke (2007);
PHOTOGRAMMETRY/	bedforms,	(+) Enables observation of evolving landscape and vegetation	Hooke and Yorke (2010; 2011);
ARCHIVAL	channel chnange	(+) Often only way to investigate past/long term evolution	Westaway et al., 2003;
IMAGES		(+) Very high spatial resolution possible with UAVs	Winterbottom and Gilvear, 1997;
		(+) Enables bathymetric mapping in clear waters	Flener et al., 2013; Legleiter, 2012;
		(-) Underwater evolution difficult to obtain	Williams et al., 2014
		(-) Often dependent on external data sources	
UAV	Topography,	(+) Rapid to perform over large and inaccessible areas	Flener et al., 2012;
	bathymetry,	(+) Higher spatial resolution compared to	Lejot et al., 2007;
	bedforms,	traditional airborn mapping	
	channel change	(+) Prices of the drones are going down	Jaakkola et al., 2010;
		(+) Can be used in various applications	Saarinen et al., 2013, 2015

		(-) Requires special expertise to perform (-) Final price depends on the attached devices	
ADCP	Flow structure, flow discarge, bathymetry, bed load discharge, suspended load, channel change	(+) Relatively easy to use (+) Enables gathering various data types at once (+) Possible to attach to a RC platform (+) Rapid, three-dimensional flow structure measurement (-) Cannot measure flow or depth in depths under 0.2 m (-) Snap-shot measurement of flow - change to errors (-) Time consuming over large areas (-) Rather expensive	Claude et al., 2014; Dinehart and Burau, 2005a; Flener et al., 2015; Gaeuman and Jacobson, 2007; Guerrero and Lamaberti, 2011; Kasvi et al., 2013a; Nystrom et al., 2007; Rennie et al., 2002; Riley and Rhoads, 2012; Williams et al., 2015
ADV	Flow structure, flow discharge	(+) Reliable (+) Three-dimensional measuerment (+) Accurate (-) Slow to perform over large areas (-) Cannot apply on deep water	Hodskinson and Ferguson, 1998; Engel and Rhoads, 2012
SIDE SCANNING SONAR	Bathymetry, bedforms channel change	(+) Rapid to perform (+) Good spatial resolution (+) Easy to use (-) inaccessible in shallow waters	Kaeser et al., 2013; Kasvi et al., 2015b; Laustrup et al., 2007; Parsons et al., 2005
CFD	Flow structure, bed load discharge, suspended load, bed forms, channel change	(+) Enables high spatial and temporal resolution and extent (+) Can be used to simulate past or hypothetical events (+) Can be used to fulfill data gaps (+) Free softwares available (-) A simplified representation of a natural phenomenon (-) Requires special expertise to perform (-) Morphodynamic models have major uncertainties (-) Computational requirements grow with increasing spatial and temporal resolution and model dimension (-) Difficult to assess reliability	Alho and Mäkinen, 2010; Kasvi, 2015b; Carling et al., 2010; Rodriguez et al., 2004; Dargahi, 2004; Hodskinson and Ferguson, 1998; Nicholas et al., 2012; Rodriguez et al., 2004; Olsen, 2003
FLUME EXPERIMENTS	Flow structure, bed load discharge, suspended load, bed forms,	(+) Enables high spatial and temporal resolution (+) Enables eliminating disturbances present in nature (+) Enables measurements in simplified environment and circumstances (+) Enables repetition (-) Requires space and major investments (-) Requires special expertise to perform (-) Not a natural environment (-) Measurements suffer from scale factors	Abad and Garcia, 2009; Blanckaert, 2009; Blanckaert, 2010; Chandler and Shiono, 2001; Lane et al., 2001; Michael and Gerhard, 2006; Nikora and Goring, 1998; Termini and Piraino, 2011

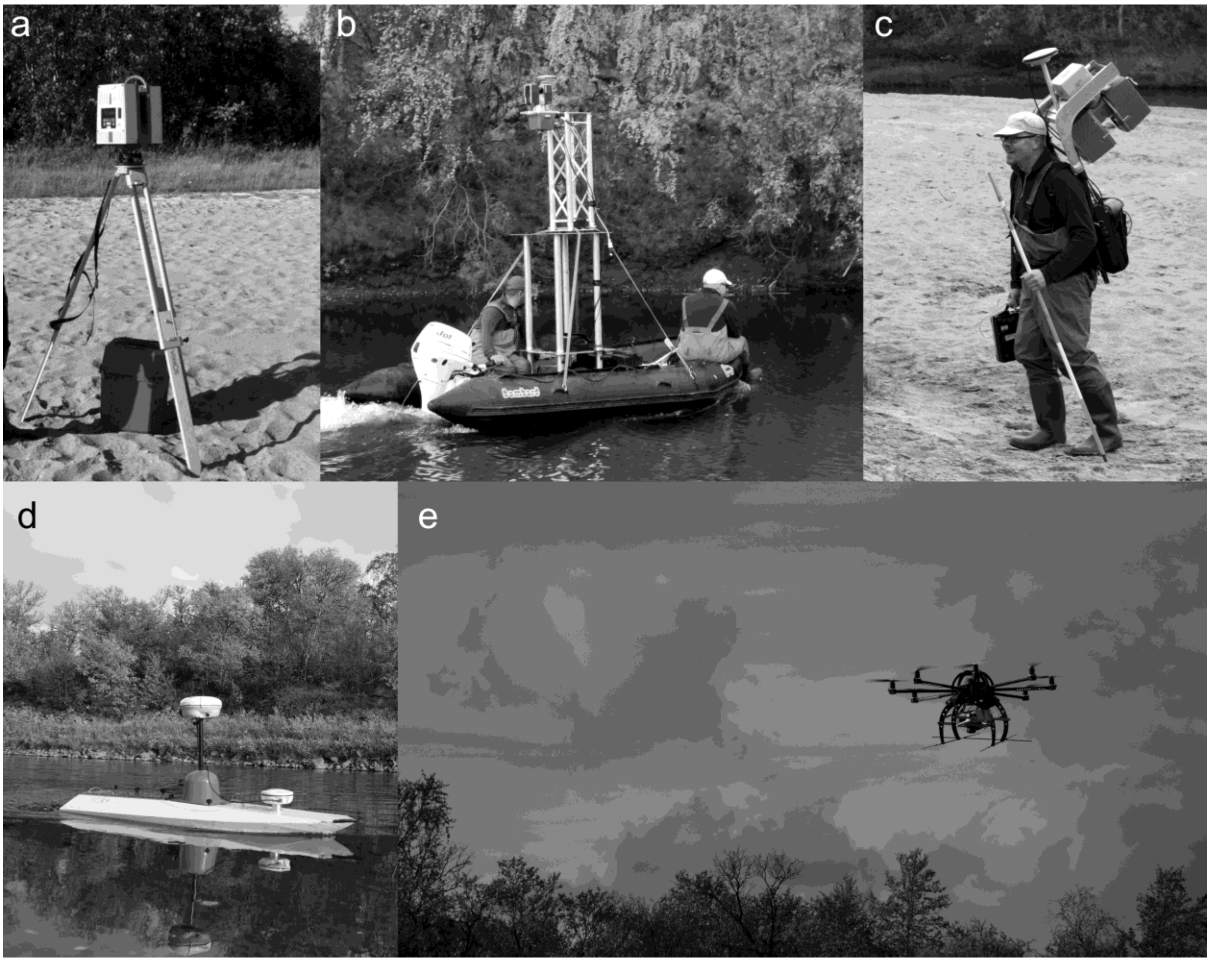

Fig 4. Examples of modern empirical measurement equipment: a) terrestrial laser scanner is used for very accurate topographical mapping; b) Boat-based mobile laser scanner is efficient in mapping river bank; c) backpack-based mobile laser scanner allows access to variety of places and enables fast collection of detailed topographic data; d) ADCP and RTK-GPS attached to remotely controlled boat allows for spatially continuous flow and bathymetric measurement; e) drones have become an increasingly popular measurement platform carrying, for example, digital cameras and laser scanners.

I Geographical information systems and positioning approaches

The emergence of geographical information systems (GIS) and the increased availability of geospatial data during the 1980s and 1990s revolutionized spatial data management and analysis; it also strongly affected the fluvial geomorphological research. Notable improvements occurred in data digitisation, overlay analyses for multiple data sets, and the amount of data that could be handled simultaneously; this led to more objective and extensive spatial analyses. Old data sets such as topographical data and maps were digitized, and they became more popular and effective (e.g. Mast et al., 1997). The data delivery also became easier. The emergence of the digital elevation models (DEMs) markedly improved observations of fluvial environments' formations, changes and processes (e.g. Brasington et al., 2000), enabling a shift from cross-sectional to spatially continuous topographical models. Simultaneously, more rapid data collection allowed higher resolution spatial data. DEMs of difference (DoDs) enabled the measurement of the volume of erosion and deposition for a surveyed area using the difference between two surveys (e.g. Lane et al., 1996; Hooke and Mant, 2000; Brasington et al., 2003a; Wheaton et al., 2010). DEMs also provided topographic boundary data for higher-order (i.e., 2D and 3D) CFD modelling (e.g. Horritt and Bates, 2002). DoDs are also starting to be used to assess numerical morphodynamics models (e.g. Kasvi et al., 2015; Williams et al., 2016).

Concurrently, developments in satellite navigation systems changed the culture of geometric data positioning, speeding up data gathering and improving positional accuracies (e.g. Brasington et al., 2000; Dunbar et al., 1999). This also accelerated the shift from cross-sectional to aerial topographical surveys. Today, an accuracy of ±1 cm can be achieved with a real-time kinematic global navigation satellite system (RTK-GNSS) using either virtual or physical reference stations (Bilker et al., 2001; Morales and Tsubouchi, 2007). A virtual reference station (VRS) in particular increases the flexibility in data collection, as it needs no physical reference station (Gao et al., 1997; Vollath, 2000; Rizos, 2002). Both GIS and satellite navigation systems provide a basis for notably more efficient spatial analysis in support of meandering river studies.

II Photogrammetry

Before the DEMs, measurements of river geometry (both topography and bathymetry) were usually realised along cross-sections over the rivers—using, for example, levelling or a theodolite (Bridge and Jarvis, 1976; Dietrich and Smith, 1983; Ferguson and Ashworth, 1992; Low, 1952; Warburton et al., 1993). These measurement campaigns were time-consuming, and their spatial and temporal resolutions were poor. The first DEMs applied in fluvial geomorphology were based on theodolite and total station measurements (e.g. Chappell et al., 2003; Fuller et al., 2003; Hooke and Mant, 2000; Kleim et al., 1999; Lane et al., 1996). With the new methods, however, the measurements are mostly limited to either a small area in detail or a large area with low spatial resolution (Heritage and Hetherington, 2007; Large and Heritage, 2009).

Airborne surveying has become more popular in the creation of topographical maps and in fluvial geomorphology, since the critical developments in analytical photogrammetry during the 1980s. It became possible to deal with oblique images and to use relatively cheap, non-metric, cameras because the images were processed and analysed mostly using computers (e.g. Barker et al., 1997a; Lane et al., 1992). Depending on the scale of the object, different photogrammetric methods can be utilised. For modelling micro-scale landforms, terrestrial photogrammetry is widely applied (Brasington et al., 2003a; Chandler et al., 2002, 2005; Haneberg et al., 2008; Lane et al., 2001; Pyle et al., 1997; Westoby et al., 2012). Photogrammetric methods, such as panoramic photography, can also be used in combination with laser scanning (Vaaja et al., 2011a).

During the 1990s, aerial photography began to be used in DEM-based topographical surveys of rivers, improving the spatial coverage of the data (Lane et al., 1994; Heritage et al., 1998; Westaway et al., 2003). Since then, airborne techniques have been exploited for a wide range of research subjects among fluvial geomorphologists, including bathymetric surveys (Bryant and Gilvear, 1999; Williams et al., 2014; Winterbottom and Gilvear, 1997) and grain-scale characterisations of rivers (Carbonneau et al., 2004; Dugdale et al., 2010). The main advantage of aerial photogrammetry is that it enables access to remote areas (Dean and Morrissey, 1988; Duncan et al., 1998) and more extensive surveys (Westaway et al., 2003).

The use of airborne photographs in sub-bend-scale studies of meandering processes has, however, been limited thus far due to the relatively low spatial resolution. Ground-based oblique photographs, by contrast, are more feasible in small spatial-scale studies (Chandler et al., 2002). Barker et al. (1997b) presented the use of terrestrial photogrammetry in measuring bank erosion in a rapidly changing fluvial environment. They took metric photographs of the river bank on several dates, enabling the generation of digital terrain models from which morphological and volumetric changes could be assessed. Since then, many other researchers have exploited terrestrial photogrammetry in fluvial geomorphological studies (Heritage et al., 1998; Hooke and Yorke, 2010, 2011; Lane et al., 2001). Chandler et al. (2008) demonstrated the use of close-range photogrammetry in determining the river-water surface level for model validation purposes, but this application has not yet been exploited much in thematically focused studies. The main issues limiting its usage are that it requires close access to the target (such as at the river bank) and that it is rather time-consuming to perform. Westoby et al. (2012) provided a good review of the recent photogrammetric developments in fluvial surveys.

Recently, unmanned aerial vehicles (UAVs), such as remotely controlled drones and helicopters, have been increasingly used for environmental monitoring and geomorphological mapping (Boike and Marzolff et al., 2003; Smith et al., 2009; Vericat et al., 2009; Yoshikawa, 2003). Due to the rapid development of low-cost drones, UAVs have been increasingly used for collecting digital images (Flener et al., 2012; Lejot et al., 2007; Jaakkola et al., 2010). A UAV enables the collection of very high-resolution georeferenced aerial photographs (0.05 m in Kasvi et al., 2015a). The resolution of the UAV-based digital images is comparable to those of terrestrial ones, but the UAV images are notably faster to collect. The UAV technique is also cost-effective, and it allows for surveys of difficult-to-access areas. Increasing numbers of fluvial studies applying UAV-based orthophotos have been carried out during the last few years (e.g. Kasvi et al 2015a; Saarinen et al., 2013, 2015).

The most recent application of digital images in the field of fluvial geomorphology is the structure-from-motion (SfM) photogrammetry (e.g. Dietrich, 2015; Smith et al., 2016). Using the SfM technique, the 3D structure of an object is resolved from a series of highly overlapping offset images which capture the full 3D structure of the scene viewed from a wide array of positions; optionally, this can be done from a moving platform. The known 3D positions of the camera and its targets are then solved automatically from a set of multiple overlapping images. SfM is commonly applied with UAV image sets to produce 3D point clouds. Within the last few years the use of SfM has been growing among fluvial geomorphologists (e.g. Fonstad et al., 2013; Javernick et al., 2014; Micheletti et al., 2014; Micheletti et al., 2015; Smith and Vericat, 2015; Westoby et al., 2012). Fonstad et al. (2013) presented DEMs produced with SfM, which were of comparable accuracy and precision to those from aerial LiDAR (light detection and ranging) data. Javernick et al. (2014) achieved even better accuracies. Micheletti et al. (2015) collected high-resolution topographic and terrain data using handheld smartphone technology and used that data to produce DTMs of fluvial environments with SfM technology; this technique had promising results. Recently, there have also been attempts to map the sediment grain-size information across large areas using the SfM technique. Westoby et al. (2015) compared the SfM images with datasets acquired using terrestrial laser scanning, and found them to be accurate to within 1.7 and 50 mm for patch- and site-scale modelling, respectively. These studies have, however, still been mainly focused on methodological demonstrations and testing. Thus, the potential of the photogrammetric methods such as SfM in fluvial geomorphology, and especially in meander dynamics studies, is still only weakly exploited, and the technique will most likely provide plenty of important new insights in the field of fluvial geomorphology in the near future. Digital photography in can also be used in bathymetric mapping (see section 4.4).

III Laser scanning techniques

The use of LiDAR applications has increased markedly during the first two decades of the 21st century particularly in the geomorphological mapping of fluvial environments (e.g. Charlton et al., 2003; Heritage and Hetherington, 2007; Hohenthal et al., 2011; Notebaert et al., 2009; Rhoads et al., 2009; Stott, 2013; Thoma et al., 2005; Williams et al., 2014). In this method, a laser scanner calculates the distance from a target to the device based on the time a laser pulse takes to travel to the target and back, using the known wavelength of the laser pulse and the phase difference of the emitted and transmitted laser beams. The main advantages of LiDAR techniques are their accuracy and speed (Hodgetts, 2009). LiDAR also allows for the measurement of areas that are difficult to access using traditional methods or even GPS (global positioning system), as it does not require physical contact with the measured object. Therefore, this method also minimises measurement errors caused by the disturbances from the measurement equipment or the measurer upon entering the study site. The main limitation of these infrared-wavelength laser scanners is that they cannot be used in bathymetric surveys (e.g. Williams et al., 2014). Laser scanning can be realised from an aircraft (i.e., airborne laser scanning, or ALS), from the ground (i.e., terrestrial laser scanning, or TLS) or from a moving platform (i.e., mobile laser scanning, or MLS). Together with high-accuracy GPS, ALS enables the gathering of detailed geometric data for rivers in substantially less time than conventional methods require (Petzold et al., 1999). ALS has been used in surveys of large areas, and it can achieve point densities of 5–50 points/m^2 and accuracies of 0.10 m to 0.50 m (e.g. Heritage and Hetherington, 2007; Höfle et al., 2009; Vosselman and Maas, 2010). In densely vegetated areas, however, it does not always give a true topographic data.

Modern TLS devices measure approximately one million points per second with an accuracy of a few millimetres (e.g. Faro, 2014; Leica Geosystems, 2014). However, the TLS method is relatively time-consuming, as only relatively small areas can be scanned at one time (Alho et al., 2009a; Williams et al., 2014). MLS was developed to overcome this disadvantage (e.g. Hyyppä et al., 2009; Kukko et al., 2007). In MLS, the scanner is mounted on a moving platform, and the laser-measured point cloud is georeferenced based on simultaneous measurements from a GNSS receiver and an inertial measurement unit (e.g. Vaaja et al*.*, 2013). Alho et al*.* (2009) demonstrated a boat-based MLS which enabled measurements in fluvial environments and the scanning of, for example, vertical channel banks. A cart (Vaaja et al*.*, 2011b) and a backpack (Wang et al*.*, 2013) have also been exploited in fluvial studies. MLS systems can produce point clouds with densities of more than 1 000 points/m^2, which is notably higher than those typically achieved with ALS (5–50 points/m^2, e.g. Höfle et al., 2009; Vosselman and Maas, 2010) or alternative field-measurement techniques. For example, Brasington et al. (2000) surveyed a reach of 200 × 80 metres with a point density of 1.1 points/m^2, and Fuller et al. (2003) achieved a point density of about 0.06 points/m^2 over an area of about 20 000 m^2 using a total station. The MLS measuring method has also proven efficient at detecting topographic changes on point bars. Vaaja et al*.* (2011b) and Kasvi et al*.* (2013a) reported an approximately 0.1-metre level of detail when the confidence limit of the change detection was 95% (based on MLS data) and a vertical RMSE of less than 0.05 m for the DTMs. TLS surveys are also used to provide reference data for MLS surveys in riverine environments (Vaaja et al*.*, 2013).

TLS and MLS are preferred in detailed geomorphological surveys, and they have been exploited to some degree in fluvial geomorphological studies, such as in high-detail surveys of morphological changes (Kasvi et al*.*, 2015a; Lotsari et al., 2014; Milan et al., 2007; Morche, 2008; Pizzuto et al., 2010), floodplain vegetation (Jalonen et al*.*, 2015), the impact of river ice on gravel transport (Lotsari et al*.*, 2015) and even grain-scale morphology and roughness (Brasington et al., 2012; Heritage and Milan, 2009; Hodge et al., 2009). A recent development in MLS is the introduction of UAV-based laser scanning (UAV-LS) (see, e.g. Lin et al*.*, 2011). In UAV-LS, the advantages of the airborne scanning platform and the flexibility of unmanned drones are combined. This method has also been used in digitising riverine environments (Mandlburger et al*.*, 2015).

IV Bathymetric surveys

Bathymetric surveys often suffer from lower spatial resolution and accuracy when compared to topographical surveys; the time required for executing a bathymetric survey increases in proportion to the spatial resolution achieved (e.g. Brasington et al., 2003b; Westaway et al., 2003).

Echo-sounding techniques became widely used in scientific bathymetric measurements During the latter half of the 20th century (Dost and Mannaerts, 2008). This was a notably more efficient method for measuring bed topography than the traditional, manual methods. An echo sounder is attached to a moving platform, and the measurement is positioned using a GPS. Today, very high-resolution and efficient devices with multiple beams are used to create detailed fluvial morphological surveys (e.g. Kaeser et al., 2013; Kasvi et al*.*, 2015b Laustrup et al., 2007; Parsons et al., 2005). Side-scanning multi-beam sonar offers the highest spatial resolution of the various sonar techniques (cf. Kasvi et al., 2015b; Parsons et al., 2005). However, the achieved point spacing is typically more than 0.2 m, so more flow depth (about 0.5 m) is required than in other sonar approaches (e.g. Kaeser et al., 2013; Parsons et al., 2005). Thus, its usage is limited to medium and large rivers. Flener et al. (2015) demonstrated a measurement approach in which the ADCP device was attached to a remotely controlled mini-boat that was equipped with RTK-GPS. They measured the bathymetry and flow field with a point density of roughly 0.7 points/m^2. This achieved point density can be enhanced by spending more time on the survey, but the method's disadvantage is its changing flow conditions and continuously evolving bedforms, just like those found in traditional survey methods. In shallow areas, a remotely controlled boat can be used to notably extend the measurement area (Flener et al., 2015; Kasvi et al., 2017). Echo sounders do not, however, measure depths of less than 0.2 m; so very shallow areas, such as meander point bars, can be difficult or even impossible to survey *in situ* without disturbing the bed forms.

Attempts to use optical photogrammetric approaches in bathymetric mapping have emerged (e.g. Westaway et al., 2003; Winterbottom and Gilvear, 1997), and recently, they have shown high potential for closing the existing gap between topographical and bathymetric data resolution, thus enabling the creation of seamless DEMs of the river channel (e.g. Flener et al., 2013; Legleiter, 2012; Williams et al., 2014). Optical bathymetric mapping is based on the assumption that spectral radiance from the wetted channel bed captured by photogrammetric methods is related to depth (Feurer et al., 2008; Marcus and Fonstad, 2008). Flener et al. (2013) successfully produced a seamless DEM of a meander bend by combining an MLS-based DEM of a point bar with a bathymetric model based on a high-resolution (5-cm cell size) UAV-based digital image. The root mean squared error (RMSE) of the bathymetric model varied between 8 and 10 cm, thus not yet being comparable to the topographical surveys. However, their study was methodologically focused, and thus, the seamless model was not used to analyse meander dynamics. Also, the other examples mentioned above, even though performed in braided river environments, focused mostly on methodological development and therefore have not yet been exploited much in increasing the scientific understanding of river dynamics.

In several earlier studies related to laser scanning, a green wavelength laser was implemented in airborne bathymetry systems (e.g. Hilldale and Raff, 2008). Smith et al. (2012) presented the development of laser scanning sensors with green-light wavelengths in TLS systems, which improved the applicability of bathymetric LiDAR in fluvial studies. They discussed a wide range of potential applications and limiting factors. However, bathymetric LiDAR has been used mainly in clear-water marine environments, not much in rivers, so it still needs to be developed further, particularly for the mapping of shallow water areas and turbid environments.

V Measuring the flow and sediment transport patterns

In the early studies of fluvial geomorphology, the flow structure was measured in one dimension using a mechanical or electromagnetic current meter, and the discharge calculation was based on velocity measurements. Using these methods, general theories describing the flow patterns of meander bends, still considered valid today, were established (Bathurst et al., 1977, 1979; Bridge and Jarvis, 1976; Dietrich et al., 1979; Dietrich and Smith, 1983, 1984; Thorne et al., 1985). Also, some detailed investigations of the spatial distribution of the flow and sediment transport patterns over a meander point bar were implemented (see Bathurst et al., 1977; Dietrich et al., 1979; Dietrich and Smith, 1983).

With the emergence of acoustic measurement technologies, e.g. acoustic Doppler velocimeters (ADV) and acoustic Doppler current profilers (ADCP), 3D velocity data gathering became possible (e.g. Hodskinson and Ferguson, 1998). Acoustic techniques measure 3D flow velocities using the Doppler shift principle. The ADV is used to measure the flow field at an individual point, while the ADCP can measure the flow field within a water column and discharge from a moving platform. During the 1990s, only ADVs were used to measure 3D flow fields in shallow rivers (e.g. Voulgaris and Trowbridge, 1998), while the use of ADCPs was limited to deep rivers because of the large blanking depth and poor vertical resolution (e.g. Simpson et al., 1990). Since then, acoustic technologies have improved and the ADCP can nowadays be applied in shallow waters as well (depth more than 0.3 m). The ADCP is especially functional when performing measurements in a rapidly changing discharge, as it can be operated from a moving platform. It also enables detailed flow-field measurements in deep waters (compared to the ADV, e.g. Rehmel et al., 2007) and records the bathymetry of the riverbed simultaneously (e.g. Riley and Rhoads, 2012). This has led to an emergence of a wide range of studies exploiting the ADCP and dealing with flow structure and turbulence, as deep rivers that are inaccessible on foot can also be investigated (Claude et al., 2014; Dinehart and Burau, 2005a; Guerrero and Lamaberti, 2011; Kasvi et al., 2013a; Nystrom et al., 2007; Rennie and Church, 2010; Riley and Rhoads, 2012).

Even though transect-based ADCP measurements are much more efficient compared to traditional methods and allow for investigations in deep rivers as well, their added value to the understanding of riverine processes has been limited. Compared to traditional methods, they have mainly the same disadvantages, namely the fact that, in transect-based approaches, most of the spatial area is not surveyed, and thus, the results are highly dependent on the analysis of the data. Therefore, recent attempts have been made to map the flow field in high resolution with spatially continuous ADCP data (cf. Flener et al., 2015; Williams et al., 2013, 2015).

Flener et al. (2015) demonstrated a measurement approach in which the ADCP device was attached to a remotely controlled mini-boat equipped with RTK-GPS. The approach allows for spatially dense flow and bed-level measurements in a relatively short period of time. They measured a meander bend 230 meters in length and 20 to 55 meters in width, with a point density of roughly 0.7 points/m^2. The daily survey was performed nine times during one flood event and the data were interpolated and visualised in 3D. Kasvi et al.

(2017) further exploited the data in fluvio-geomorphological analysis and linked the daily morphological changes to the flow field.

Acoustic flow measurement techniques have been applied in quantifying bed-load-transport velocities and magnitudes as well, with promising results (e.g. Gaeuman and Jacobson, 2007; Rennie et al., 2002; Williams et al., 2015). The bed-load velocity can be measured by comparing the bottom-track-based estimates of sensor velocity and GPS observations (Rennie et al., 2002). By concurrently sampling the bed-load-transport rate at the points with stationary ADCP measurements, correlations between the bed-load velocity and bed-load-transport rate can be found (e.g. Rennie and Villard, 2004). Studies assessing the accuracy of the method, for example, by comparing the measurement results with bed-form migration rates (Gaeuman and Jacobson, 2007), state that it clearly improves the reliability of the bed-load measurements. When operating the ADCP from a moving platform, data collection is rapid, and spatially continuous data collection is possible (e.g. Riley and Rhoads, 2012; Williams et al., 2015). This technique is much less labour intensive compared to traditional bed-load sample collection, it does not disturb the sediment transport and it enables bed-load measurements also in high flows, which is impossible with, for example, a Helley-Smith sampler. By applying this technique, Williams et al. (2015) were able to link the spatial patterns of the bed-load transport pathways, hydraulic patterns and morphological change in a braided river reach without the flow conditions changing.

Additionally, while recording velocity, the ADCP records the intensity of acoustic backscatter from the flow. After correction for radial spreading and fluid absorption, backscatter intensity varies primarily with the volume concentration of particles suspended in the flow (Gordon, 1996). Thus, if the ADCP output is normalised and calibrated to sediment-concentration samples, the sediment concentration in the flowing water (e.g. the suspended load) can be estimated from the ADCP data. Kostachuck et al. (2005) demonstrated a use of ADCP to measure simultaneously the bed-load velocity and suspended-sediment concentration. Quality assessment tests by Guerrero et al. (2011, 2012) have given promising results about the reliability of this method.

VI Experimental studies

Flume studies have always been useful in increasing the understanding of the basic processes and cause-effect relationships of certain factors, as the rest of the disturbing factors can be eliminated (e.g. Rozowskii, 1957). As the laboratory tests are performed in controlled environments and are typically relatively small in area, they have not advanced as much from recent technical developments compared to field and computational studies. However, some empirical method development has improved the laboratory tests as well (e.g. Blanckaert, 2010). For example, use of line laser scanners has become a standard method for accurately measuring the morphology of the laboratory channel (e.g. Dijk et al., 2012; van de Lageweg et al., 2014; Michael and Gerhard, 2006). DoDs with down to a 0.2-mm cell size and 0.7-mm vertical resolution are achieved. This enables the determination of very-small-scale morphological changes. Close-range photogrammetry has also been applied to accurately, rapidly and cost efficiently measure the flume surfaces (e.g. Chandler and Shiono, 2001; Lane et al., 2001). Electromagnetic flow meters and point-type ADV devices are used to measure the 3D flow field accurately in the experimental channels (e.g. Abad and Garcia, 2009a; Blanckaert, 2009; Michael and Gerhard, 2006; Nikora and Goring, 1998; Termini and Piraino, 2011), and sonar transducers are used in bed-morphology measurements (e.g. Abad and Garcia, 2009b). Also a particle image velocimetry (PIV) system, based on the recording of particles movement in the flow, has been developed to measure velocity fields accurately in flumes (e.g. Meinhart et al., 1999). It has become popular especially in measuring turbulent flows (e.g. Druault et al., 2015).

VII Theoretical and computational approaches

Theoretical models describing meandering rivers' behaviour have been developed since the 1970s. The flow structure in bends (e.g. Smith and McLean 1984; Nelson and Smith 1989; Hodskinson and Ferguson 1998), the evolution of bend planforms (e.g. Parker 1976; Fredsøe 1978; Ikeda et al. 1981; Johannesson and Parker 1989) and sediment sorting and architecture (e.g. Bridge 1978; Parker and Andrews 1985; Bridge 1992) have been modelled successfully.

The emergence of GIS and the increase in computational power have boosted the application of multidimensional models (2D and 3D) in simulating spatially and temporally variable flow and sedimentary patterns in natural rivers (e.g. Carling et al., 2010; Kasvi et al., 2015b; Rodriguez et al., 2004). Also, the improvements made in empirical-measurement techniques have enabled a more detailed construction and validation of simulations. This has widened greatly the research questions to which the hydraulic models are applied. In the case of a multidimensional model, the river-channel geometry is represented as a grid, and the fluid motion is resolved in each grid cell over a series of boundary conditions, which may change in time. A 2D model simulates only the depth-averaged flow velocity and direction while a 3D model simulates also the vertical flow motion in a 3D grid as well. However, the computational grids are too coarse to resolve turbulent fluctuations, and thus CFD models are introduced with additional terms, which represent the effects of the turbulence on the mean flow. Constant values may be defined for the turbulence, or they may be computed using a turbulence closure model. The turbulence closure models have been implemented to better describe the transport of turbulence by the mean flow, in other words to overcome the limitation of a constant value approaches (Rodi, 1980; Lane, 1998).

The simulations of processes in natural rivers are important as the empirical measurement techniques still mostly allow only for snap-shot measurements, and, considering that continuous recording would be possible in some circumstances, the spatial coverage would probably be poor. Their evident advantages are the high spatial and temporal resolution as well as the possibility of simulating past (e.g. Carling et al., 2010) or hypothetical and future events (Lotsari et al., 2010). Thus, even though simulated processes should always be treated as simplified representations of the natural phenomena (Bates, 2004; Hardy et al., 2003; Nicholas, 2003; Rodriguez et al., 2004), they are suitable in supporting the field measurements and in enabling the fluvial morphological analysis of natural environments over remote areas, where continuous measurements of flow and sediment transport are not possible (Kasvi et al*.,* 2015a,b).

2D or even 3D model is required especially in curved channels, with a highly 3D flow field (e.g. Camporale et al*.*, 2007; Lane et al*.*, 1999; Nicholas, 2013). It has been stated that a 2D scheme cannot give a correct description of the flow field when either the bend curvature is high or the aspect ratio is too low (Camporale et al*.*, 2007). Furthermore, the limitations of the 2D model are emphasised downstream of the apex (Alho and Mäkinen, 2010; Kasvi, 2015b), where, for example, the near-bed inward flow plays an important role in the point-bar deposition. However, as the 3D model is computationally much more expensive, a 2D model with a secondary circulation sub-model aiming to achieve the more correct estimation of the real 3D flow field may be applied (e.g. van Berdegom, 1947; Blanckaert and de Vriend, 2003; Nicholas, 2013; Rodriguez et al., 2004; Rozowskii, 1957; Schuurman et al., 2013). As a 3D model solves also the vertical-flow velocities and spiral flows, it is the most suitable approach when modelling complex riverine flow fields, such as recirculation zones, which are present in meandering streams (Lane et al., 1999; Rodriguez et al., 2004). However, its computational expensiveness has limited its usage to rather short reaches thus far.

Qquasi-3D approach enables the modelling of 3D flow structures and consequent morphodynamics to a certain level, but it is computationally much more efficient to run compared to a fully 3D model. In a quasi-3D model, the vertical momentum equation is reduced to the hydrostatic pressure equation, following the shallow water assumption, as the vertical accelerations can be assumed to be small compared to gravitational acceleration. The turbulent fluctuations are still mostly handled as a sub-grid scale process and thus modelled based on semi-empirical parameterisation (e.g. Bradbrook et al., 1998; Lesser et al., 2004; Lien and Leschziner, 1994; Rüther and Olsen, 2007; Yakhot et al., 1992).

I Hydrodynamic simulations

Despite the new possibilities in flow data collection in the field, achieving a high spatial resolution of the data is still time consuming, and covering large areas without the discharge changing may thus be impossible. Therefore, CFD has provided a very beneficial alternative way of modelling the flow structure in natural rivers and real flow events with high spatial and temporal resolution. The hydrodynamic component of the model describes the flow field and provides the shear stresses near the bed. These are the driving force behind the morphology component, which describes the adaptation of the riverbed (Ottewanger et al*.*, 2012). Many of the CFD-based studies have assessed the model’s reliability by comparing the results with field or laboratory-based flow structure data. In general, they have shown rather good correspondence with the measured data: Models have successfully simulated the general flow field, flow redistribution and the secondary flow in meander bends (e.g. Dargahi, 2004; Hodskinson and Ferguson, 1998; Nicholas et al., 2012; Rodriguez et al., 2004). Some studies have used CFD to increase the understanding of the meander-bend processes.

II Morphodynamic simulations

Sediment transport is calculated based on the solutions of the hydrodynamic equations using one of the many established equations (e.g. Engelund and Hansen, 1967; van Rijn, 1984a,b), and the bed update may be calculated based on the sediment transport in each grid cell. Compared to the hydrodynamic model, the morphodynamic models have even more sources of uncertainty (e.g. Pinto et al., 2006).

Darby et al. (2002) modelled bank erosion and channel migration and assessed the modelling results with flume- and field-based data. Their results were encouraging, but some deficiencies in the model predictions were highlighted. Kasvi et al. (2015b) simulated morphological changes during one flood event in a natural meander bend and compared their results with detailed field measurements. Their results indicated that modelling short-term morphological changes still has major uncertainties. According to their study, the uncertainties are related to difficulties in calibration and validation as well as to the correct determination of the user-defined parameters, which are used to adjust and control many processes in the models. This has been noticed in many other studies as well (Bates et al., 1998; Horritt et al., 2006; Lane et al., 1999; Schuurman et al., 2013; Wilson et al., 2003). Examples of user-defined parameters are grain-size distribution, roughness, the transverse bed-slope effect, secondary flow and sediment-transport relation.

As example of this is that many studies have shown that grain-size parameterisation, used as the initial sediment size in the morphodynamic model, is critical when simulating morphological changes in various environments (e.g. Kasvi et al., 2015b; Lotsari et al., 2014a; Nicholas, 2000, 2013, Papanicolaou et al., 2008; Pinto et al., 2006). The commonly used uniform grain-size value over the modelling area in sediment-transport equations has been noted to lead to erroneous sediment-transport and morphological-change magnitudes (Nicholas, 2000, 2013; Papanicolaou et al., 2008). Also, the choice of the sediment-transport algorithm has been found to have an important effect on the modelled morphodynamics (Kasvi et al., 2015b; Pinto et al., 2006). Kasvi et al. (2015b) tested 2D and 3D morphodynamic models' sensitivity to various user-defined parameters in a natural meandering river. Based on their sensitivity analysis, roughness parameterisation influences the spatial distribution of flow velocities in a river bend and therefore the morphodynamics. When using the Chezy roughness, the roughness height is related to water depth. When a uniform Chezy roughness is applied over the entire modelling area, the roughness height over the point bars remains lower compared to the pools. This leads to a lower point-bar height and a smaller pool depth compared with other roughness parameterisation methods (Kasvi et al., 2015b). Kasvi et al.`s (2015b) study also showed that depth averaging had a significant effect on the erosional power of the flow (e.g. bed shear stress), but its implications for morphodynamic reconstruction were not notable when comparing the 2D and 3D approaches. Lesser et al. (2004), Nicholas (2003), and Schuurman et al. (2013) also stated that roughness parameterisations have a significant effect on bed morphology. The transverse bed-slope-effect parameterisation and the selected sediment-transport relation have a notable effect on the morphodynamics (Schuurman et al., 2013; Kasvi et al., 2015b; Williams et al., 2016). The co-effect of the parameters has not been tested to a wide extent thus far, and needs further investigation. For example, the suspended load is not modelled separately in all of the transport relations (e.g. Engelund and Hanasen, 1967). In that case, the underestimation of suspended-load transport would directly diminish the importance of the secondary-flow correction, as the secondary currents transport the suspended load mostly. The modelled bed-load-transport rate, on the other hand, is strongly related to the transverse bed-load effect (Nicholas, 2013).

The models\` ability to predict the near bank shear stresses have a great importance in physics-based bank erosion models, especially in meandering rivers. The main problems related to bank erosion modelling have been the lack of a physical basis, great field data requirements and an assumption of a constant river channel width (e.g., Abad and Garcia, 2006; Parker et al., 2011; Brice, 1982; Lagasse et al., 2004, Eke et al., 2014). Developments regarding bank erosion models are ongoing (e.g. Eke et al., 2014).

VI Discussion

This review has gathered recent internationally significant studies applying modern empirical and modelling approaches in the field of the fluvial geomorphology of meander bends (Table 2). It is clear that major developments in theory and modelling techniques have taken place within the past couple of decades (e.g. Hooke et al., 2011), but in this study, we have taken a closer look at the extent to which fluvial geomorphologists have exploited the opportunities that the new techniques have provided, and, more precisely, to elucidate sub-bend scale meander dynamics. Meandering rivers represent very complex 3D flow and sedimentary processes, which are regarded as relatively well studied and understood. After a rather quiet era in meandering research since the 1980s, an increasing number of empirical, theoretical and CFD-based studies aimed at deepening the understanding of meander dynamics have been published. One of the most evident advantages of the new empirical methods from a fluvial morphological point of view is the possibility of bringing to the forefront the individual characteristics of bends and their flow and sediment patterns. The traditionally used cross-sectional measurements of the river geometry (e.g. Dietrich and Smith, 1983; Ferguson and Ashworth, 1992; Frothingham and Rhoads, 2003; Warburton et al., 1993) and DEMs produced with more traditional methods, often presuming a trade-off between spatial extensiveness and spatial resolution (Brasington et al., 2000; Heritage et al., 1998; Lane et al., 1994), may lead to a discontinuous picture of the river reach and possibly to an incorrect interpretation of the phenomenon (Heritage and Hetherington, 2007).

The importance of the spatial coverage and accuracy of the geometrical data has been noted in many previous studies (e.g. Bates, 2004; Brasington et al., 2000; Heritage and Hetherington, 2007). Approaches such as TLS and MLS (e.g. Alho et al*.,* 2009a), terrestrial photogrammetry (e.g. Westoby et al., 2012) and SfM photogrammetry (Micheletti et al., 2015) have enabled notably more efficient surveys of riverine topographies, compared to conventional methods, with very high spatial resolution (Table 1). UAVs have provided a cost-efficient platform for performing high-resolution photogrammetric surveys, which has led to a new emergence of studies exploiting photogrammetric methods in fluvial geomorphology (e.g. Flener et al., 2012). The spatial resolution and coverage of riverine bathymetric data have been enhanced by the echo sounders and the more advanced implementations of them, such as side scanning sonars (Parsons et al., 2005) and sonars attached to remote-controlled mini-boats (Flener et al., 2015). Lately, optical bathymetric modelling from high-resolution digital images have become possible as well in the wake of the increased availability of UAVs (Flener et al., 2013). Acoustic techniques (ADCP and ADV) have increased the reliability, effectiveness, spatial and temporal coverage, and accessibility of flow-structure surveys (Kasvi et al*.,* 2013a) as well as the measurements of sediment-transport patterns (Williams et al*.,* 2015). Spatially continuous flow-structure measurements have been performed using a remote-controlled platform (Kasvi et al., 2017). Also, experimental studies have profited from the progress of empirical-measurement techniques (e.g. Van de Lageweg et al., 2014). Multidimensional CFD has become a feasible approach to model flow distribution and sediment transport also in natural streams (e.g. Kasvi et al*.,* 2013b, 2015a), and several related open-source CFD software has been released.

The recent methodological development has provided possibilities to gain new insights in the governing factors in meander bends, related to both fluvial and morphological processes (Table 2). Some of the outcomes are highlighted below.

Table 2. Recent meandering studies applying modern methods and techniques and their main outcomes.

	Study approach	Flow structure	Sediment dynamics	Channel change	Applied methods	Main outcomes
of bend orientation ructure and	Flume study	X			ADV	In upstream valley flow is not as w downstream val
sharp meander	Flume study	X			ADV	Outer-bank secon shelving banks a steepness, espe
nulation of bank d channel n meandering	CFD	X	X	X	CFD, validated with flume and field data	Model can accurat of the bed topo predicted by the in flume experi qualitative, rath bed topography
-morphology in ompound meander	Field study	X		X	ADV, total station, RTK-GNSS	Bank erosion and near-bank veloc factors, includin bars and failed b on near-bank fl
der bends with recirculation	CFD of natural river	X			CFD, electromagnetic current meter, ADV, total station, pebble count	High planform cur separation to o recirculation. C with separation
loodplain sediment n rapidly migrating	Field study		X	X	Echo sounder, RTK-GNSS, total station	Sedimentation on external factors Flood intensity, sediment conce meander defor
ander morphology dal timescales	Aerial photography and annual field mapping			X	Aerial photography, GIS, terrestrial photographs, field observations	Bends exhibit an a qualitative mod of bank-line mo sequence until t decrease. Proce related to disch
le flow–sediment of meander bends	Field study, CFD	X	X	X	TLS, MLS, CFD, ADCP	The influence of a depends on the

	Study approach	Flow structure	Sediment dynamics	Channel change	Applied methods	Main out
	Field study	X		X	TLS, MLS, ADCP	The dura impor effects deposi evolut indepe
low river	CFD	X			CFD	The flow topogi secon the hy curved
ough a er	CFD of natural river	X			CFD, validation data with ADV	2-D mod the m field. T locate Pools of high
on in a	Flume study	X			ADV	Counter- the ca begins develo counte shear
	Flume study		X	X	Line laser scanner	Width va explain

I Sub-bend scale flow structures and their controlling factors

During recent years, the flow structures of meander bend have been mostly studied using acoustic methods (ADCP, ADV), in laboratory flumes and using computational modelling. Thus far, ADCP surveys of meandering-river flow patterns have been carried out mostly along a series of river transects (e.g. Dinehart and Burau, 2005a; Kasvi et al., 2013a). For the most part, the results gained with modern methods have supported earlier studies. A clear secondary circulation of flow, for example, has been reported in some field studies (Dinehart and Burau, 2005a; Engel and Rhoads, 2012; Kasvi et al., 2013a). Efficient data collection has also enabled measurements with different flow stages of the same flood event to investigate changes in the flow patterns. Engel and Rhoads (2012) studied the interaction of flow and bed morphology in a compound meander bend by combining channel-change surveys with ADV measurements of 3D flow velocity. Their data showed that local factors, including the deflection of the flow by point bars and failed bank blocks, enhance or inhibit the development of high near-bank velocities and turbulence kinetic energy. Kasvi et al. (2013a) measured the flow structure in a meander bend during different discharges and linked the measurements to high-spatial-resolution morphological change detection. They showed that the flow stage has a major impact on the flow structure and on the spatial distribution of the flow velocity and stream power and therefore also on morphological changes. According to their measurements

(Engel and Rhoads, 2012; Kasvi et al., 2013a), a decrease in depth over the point bar increases the effect of the point bar upon the flow trajectory. The data of Kasvi et al. (2013a) also supported the findings of Hooke (1975) and Dietrich and Smith (1983) that the transverse shift of the HVC is controlled by changes in the discharge and flow depth, which are usually interconnected. This leads to the transverse shift of the HVC further upstream during a moderate discharge compared to a high discharge.

The effects of bend parameters, such as curvature, amplitude and width to depth ratio, on the flow structure have been studied experimentally and computationally. Rodriquez et al. (2004) showed, using CFD, that the helical flow structure caused the near-bed-flow velocities to be stronger downstream of the bend apex compared to the upstream part. This is called the submergence of the high-velocity core. CFD has also made it possible to verify the assumption that bend deformation has implications for the flow over the bend, such as the bend curvature and point-bar geometry effect on the secondary-flow formation and location of the HVC (e.g. Kasvi et al., 2013b, 2015a; Ottewanger et al., 2012). Further, Blanckaert and de Vriend (2003) showed that the commonly used secondary-flow parameterisations used in CFD, which assume weak-curvature variations, considerably overestimate the secondary flow in moderately and sharply curved bends, as they neglect the nonlinear interactions between the streamwise flow and the secondary flow. Therefore, Blanckaert and de Vriend (2003, 2010) developed and validated a nonlinear reduced-order hydrodynamic model that successfully simulates the saturation of the secondary flow by extending the parameterisation of the secondary flow to sharply curved bends. They stated that streamwise variations in curvature are a dominant driving force of the velocity redistribution in sharply curved bends. By exploiting the model by Blanckaert and de Vriend (2003, 2010), Ottewanger et al. (2012) showed that major differences exist between the hydrodynamic processes in mildly and sharply curved bends. They showed that secondary circulation strengthens with increased bend curvature but saturates in sharp bends and increases in strength in proportion to the discharge.

Termini and Piraino (2011) studied experimentally the detailed flow structures in a large-amplitude channel. Their study showed that the counter-rotating circulation cell is evident only in the case of a ‘small’ width-to-depth ratio and that the presence of the counter-rotating circulation cell allows the bank shear stress to maintain low values on the outer side of the bend. They also stated that the secondary cell diminishes in very high discharges and does not form with a large width-to-depth ratio. Blanckaert (2009) studied the curvature-induced secondary flow and showed that the secondary flow does not increase when the curvature is increased in very sharp bends; he called this process the saturation of the secondary flow. This may inhibit the meander migration (Blanckaert, 2011). Abad and Garcia (2009a, 2009b) studied the effect of bend skewness and orientation on the flow structure and bed morphodynamics. Their measurements showed, for example, that when bends are oriented upstream, the secondary flow is not as well developed as in the case where bends are oriented downstream. Furthermore, the experiments by Abad and Garcia (2009b) showed that in bends oriented upstream, the bed forms are produced just upstream of the bend apex, whereas for the case of bends oriented downstream, they are observed around the upstream inflection point.

II New insights to sub-bend scale morphodynamics and some indications to longer term development

Recent studies exploiting contemporary research approaches have observed many fluvio-geomorphological processes which are generic for meandering rivers (Ferguson et al., 2003; Frothingham and Rhoads, 2003; Engel and Rhoads, 2012). Hooke (2007) and Hooke and Yorke (2010; 2011) used archival aerial images together with terrestrial photography and flow records to analyse the mechanics of change in meander bends. These unique studies indicated that bends in natural rivers exhibit morphological changes that largely follow the qualitative models of meander development (e.g. Brice, 1974). Also Engel and Rhoads (2012) showed in their study based on ADCP measurements, that the studied compound meander loop became more asymmetrical over time, supporting the conceptual models according to which the compound loops evolve continuously over time rather than developing into a stable configuration (e.g. Brice, 1974). A field study by Riley and Rhoads (2012), applying ADCP in a confluent meander bend showed that the flow patterns were quite different from typical patterns in most meander bends but were generally consistent with a conceptual model of confluent meander bends (Roberts, 2004).

The recent studies have also highlighted that meandering rivers are complex systems with nonlinear and unique behaviour (Gautier et al., 2010; Hooke and Yorke, 2011; Hooke, 2007a; Kasvi et al., 2013a, 2015a). They have shown that the individual characteristics of bends and the local factors of streams may have a strong influence on the fluvio-geomorphological processes of the meander bends and on the evolution of the river (e.g. Gautier et al., 2010; Hooke, 2007b; Hooke and Yorke, 2011; Kleinhans and van den Berg, 2011; Seminara, 2010). Combining digitised archival images, terrestrial digital photographs and flow data allowed Hooke (2007) and Hooke and Yorke (2010, 2011) to retrieve important new insights into meander dynamics. Their long-term studies proved that no clear association of changes in one bend with another exists and that the channel morphology itself has a notable impact on the morphological changes experienced over the bend. Hooke and Yorke (2010) also showed that morphological changes, which vary in space and time, take place in phases which are related not just to discharge but also to inherent sequences and feedbacks. Based on this type of analysis however, the bar activity is related to discharge events and phases (Hooke and Yorke, 2011),.

Recent studies have also gained varying results of the connection between the net morphological change of a point bar and the peak discharge magnitude. Terrestrial and mobile laser scanning have enabled a very detailed interpretation of the spatial patterns of net erosion and deposition formations in meander bends (e.g. Kasvi et al., 2013a, 2015a; Lotsari et al., 2015). Kasvi et al. (2013a) used MLS to study the flood-based channel changes and measured the flow structure data using ADCP. On the same meandering river reach, Kasvi et al. (2015a) combined the MLS-based morphological surveys with computationally simulated flow data over flood events. Lotsari et al*.* (2014b) studied the annual bank and point-bar morphodynamics of eight consecutive bends of a 3.7-km reach of the same river between 2009 and 2012 using MLS data. According to the measurements of Lotsari et al. (2014b) the area of net deposition over point bars is larger with a higher spring-flood-discharge magnitude. However, a temporal analysis by Kasvi et al. (2017) indicated that flood duration and the rate of discharge increase and decrease seem to play key roles in determining channel changes by controlling the flow velocities and depth. According to Kasvi et al*.* (2013a, 2015a) the annual variation in the sediment budgets of a single point bar can be considerable, and the spatial patterns of the net erosion and net deposition caused by a certain flood event can vary considerably between point bars within a reach. Kasvi et al. (2015a) showed that the point-bar margins are characterised by long inundation periods that include both high- and low-discharge periods and stream powers. Thus, the period of moderate discharges during the flood's descent has a major impact on the point-bar accretion. The processes over the point-bar head are especially interconnected to the shift of the HVC, which is dependent on the flow stage. Thus, even though many studies and conceptual models of meander development (Gautier et al., 2010; Hooke, 1975; McGower and Garner, 1970) state that the point-bar head is an area of net erosion, their (e.g. Kasvi et al*.*, 2015a) study showed that as the discharge decreases, the outward shift of the HVC reduces the stream power over the bar head, thus enabling filling to occur over the bar head during moderate and low discharges. The morphological changes caused by previous flood events have also been noted to affect the erosion and deposition caused by the following floods (Gautier et al., 2010), which might be one factor controlling the spatial patterns of the changes.

As bathymetric surveys often suffer from lower spatial resolution and accuracy when compared to topographical surveys, the morphodynamics of the inundated areas have been challenging to study, especially in the field. Kasvi et al. (2017) performed a spatially and temporally (daily) intensive field survey over a meander bend with an ADCP attached to a remotely controlled mini-boat. They studied the spatial patterns of morphological activity and linked them to flow patterns. Their data showed that both erosion and deposition occurred throughout the flood, but magnitudes of the morphological changes (both erosion and deposoition) were more notable during periods of high- compared to low-discharge periods. Their measurements also indicated that a long duration of high stream power may have a hindering effect on point-bar growth and thereby meander evolution.

Several attempts have been made to model the meander bend morphodynamics. Crosato and Mosselman (2009) developed a physics-based method for predicting the number of river bars; and Crosato (2009) derived physical explanations of meander migration rates. Both 2D (Duan and Julien, 2005) and 3D (e.g. Olsen, 2003) models have been used to compute the formation of meandering rivers in initially straight alluvial channels. Olsen (2003) tested a CFD model by comparing it with results from a flume study. The model successfully replicated many of the meander characteristics, including secondary currents, cross-sectional profiles, meander planform, meander wavelength, downstream meander migration and chute formation. Duan and Julien (2010) successfully simulated downstream and upstream migration, lateral extension, and the rotation of meander bends using a 2D model. Chen and Duan (2008) simulated meander migration during 12 years in a natural meandering channel using a depth-averaged model with good correspondence with field measurements. Kasvi et al., (2015b), however, showed that sub-bend scale morphological changes in a natural meander bend are challenging to model, as they are affected by factors that have been neglected in the simulations. That is probably the reason why the morphodynamic models are still used rather infrequently today in solving fluvio-geomorphological research questions of natural rivers. However, Kasvi et al*.* (2015a) simulated the sediment transport over three meander bends during a flood event with a 2D model and validated the sediment transport magnitudes with field measurements. They stated that whether net erosion or net deposition occurs in one part of a meander point bar depends on the following factors at least: The relative differences in stream power, cross-stream flow components, flow depth, flow velocity, the duration of each discharge, grain-size distribution and the stage of the bend development. They found that the magnitude of the sediment transport and the net morphological change over a certain part of a point bar are not interconnected: Areas of net erosion and deposition may have experienced either high or low sediment-transport rates during the flood event.

Currently, there is an ongoing debate about whether the increase in bend sinuosity and thereby the meander evolution is driven by bank pull or bar push. Laboratory, modelling, and field based studies have been realized. Van de Lageweg et al. (2014) studied experimentally whether the scroll-bar formation forms in response to the bank pull or bar push. They were able to isolate the effects of sediment supply on the point bar, bank protection and forced bank retreat. Based on their study, they stated that channel-width variations along meander bends cause bank pull, which is necessary for scroll-bar formation. Various studies have stated that outer bank erosion is the leading process in meander migration, followed by point-bar growth (e.g. Hooke, 2007; Gautier et al., 2010; Eke et al., 2013). By contrast, Schuurman et al. (2016) stated, based on three numerical morphodynamic models, that inner bank push is required for the development of high-sinuosity meanders. Investigating this phenomenon and the mechanisms governing the increase in bend sinuosity requires detailed sub-bend scale observations and measurements during several years. With the contemporary research approaches, new insights to these questions are expected in near future.

VII Conclusions

A wide range of new insights into meander dynamics, provided by modern techniques have been presented. We have demonstrated what increased spatial and temporal resolution of data collection enables. Many of the techniques, however, remain unutilised as yet. Most of the studies including advanced methods are still demonstrating methodological achievements but not actually applying them to resolve a fluvio-geomorphological research question. For example, no substance-focused study has thus far utilised SfM photogrammetry to elucidate the meander bend processes. Also, only a few have used terrestrial and mobile laser scanning. The usage of computational models to support field investigations is limited to a few exceptions. Achievements in bathymetric mapping (e.g. bathymetric models and remote-controlled approaches) have hardly been used in thematic studies.

Even though outstanding methodological developments have been achieved and have been applied successfully in fluvial environments, their usage is still very limited among fluvial geomorphologists. One possible reason for this is that many of the methods require expertise that few fluvial geomorphologists have. Therefore, the successful application of advanced methods for increasing the scientific understanding of riverine processes would require dialogue and co-operation between different scientific disciplines, such as geodesy, physics and the computer sciences, and fluvial geomorphologists. In 2011, Hooke et al*.* called for more dialogue between the modelling and mathematically based community and those coming from a more geomorphologically and field-based background. Even though they (Hooke et al*.*, 2011) had already noticed some progress in this back then, based on the current study, it remains limited. In the future research of fluvial geomorphology, the scientific community should take full advantage of modern empirical and modelling approaches to elucidate the fluvial processes. Cooperation between disciplines would advance all of the stakeholders and would follow the current culture of the funding agencies as well. Computational simulation approaches should be increasingly combined with field observations to increase the temporal resolution and extent of the study and to fulfil the spatial gaps of the data. Computational reconstructions of historical events could also provide answers to longer term meander evolution. Detailed annual observations of different processes would give insights to sub-bend scale processes and the connections between the spatial and temporal scales could be found by preforming multi-scale studies.

The various new techniques to map the river morphology and bathymetry with high spatial resolution would allow for surveying several river bends within a short time period and repeating the measurements regularly. Linking these to spatially intensive flow structure data gathered by ADCP or modelled using CFD would enable much deeper understanding of the processes in the bends. Roughness and grain size distribution data could be notably enhanced with close-range remote sensing. Thereby, the full deployment of methodological achievements would allow for finding answers to the remaining questions in the fluvial geomorphology of meander bends: What controlling factors interact during meander development and how are they interconnected? Are the sub-bend-scale processes of the bends predictable or consistent? Understanding these fundamental topics would also allow for further model developments, and the probability of modelling the future river behaviour and finding answers to questions such as: “why do meandering rivers evolve differently, and what induces cut-offs?” would become closer. This all will benefit societies in the areas of, for example, river conservation, engineering and flood-protection planning.

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