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Sub-bend scale flow–sediment interaction of meander bends — A combined approach of field observations, close-range remote sensing and computational modelling

Elina Kasvi [a,*], Matti Vaaja [b], Harri Kaartinen [c], Antero Kukko [c], Anttoni Jaakkola [c], Claude Flener [a], Hannu Hyyppä [b,d], Juha Hyyppä [c], Petteri Alho [a,b]

[a] University of Turku, Department of Geography and Geology, FI-20014 Turku, Finland
[b] Aalto University, School of Engineering, Department of Real Estate, Planning and Geoinformatics, P.O. Box 15800, FI-00076 Aalto, Finland
[c] Finnish Geodetic Institute, Department of Remote Sensing and Photogrammetry, P.O. Box 15, FI-02431 Masala, Finland
[d] Helsinki Metropolia University of Applied Sciences, P.O. Box 4011, FI-00079 Metropolia, Finland

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ABSTRACT

Various field-based studies of meander development have been realised, yet fluviomorphological processes and their spatial patterns over bends are not fully understood. In this paper, the processes of three natural meander bends during a flood event are dissected using a unique study approach, which combines traditional field surveying, close-range remote sensing, and computational modelling. The combined study approach improves the spatial and temporal resolutions of the data compared to traditional survey methods, although the bathymetric data collection needs improvement. The analyses indicate that the influence of a flood on the morphological changes of point bars depends on the stage of the bend's development. The point bars may also experience lateral growth during low discharge. However, the point bar is too large a unit to find simplified relationships between the discharge and morphological changes. Instead, one should concentrate on different parts of the bend and the point bar. In general, the longer the inundation period of one part, the more probable that the area will experience net deposition. The magnitude of the sediment transport and the net morphological change are not interconnected: Areas of net erosion and deposition can experience either high or low sediment transport rates during a flood. The results are compared with earlier theories of meander development, which are also assessed.

1. Introduction

In a meander bend, the curved channel shape controls the general flow field: the high velocity core (HVC) is located at the inner bank at a bend entrance and, forced by the point bar and the bend curvature, shifts toward the outer bank pool beyond the bend apex (Dietrich et al., 1979; Ferguson et al., 2003). This induces the secondary circulation of the flow, with inward near-bed and outward near-surface flow components (e.g., Bathurst et al., 1979; Bridge and Jarvis, 1982; Termini and Piraino, 2011). At the bend entrance, an outward flow often occurs throughout the water column, upon the point bar (Dietrich and Smith, 1983). These flow structures are flow dependent: when the discharge increases, the effect of the point bar on the flow decreases, the flow straightens its way over the point bar, and the HVC meets the concave bank farther downstream compared to a lower flow stage (e.g., Dietrich and Smith, 1983). Thus, a very high discharge may also weaken the secondary flow (Bathurst et al., 1979).

The sediment transport has been found to mirror the flow structure: Coarse material is transported along the outer bank where higher stream power is located, while the inner bank bedload consists of finer material (e.g., Dietrich and Smith, 1984; Clayton and Pitlick, 2007). With an increasing discharge the spatial variability in bedload transport rates and material size is reduced and, for example, coarse particles are transported also near the inner bank (Clayton and Pitlick, 2007). The outward directed surface flow and the shift of the HVC toward the outer bank lead to scour at the concave bank causing the bank to shift outward (e.g., Frothingham and Rhoads, 2003). At the same time, the high flow velocities cause erosion over the point bar head (McGowen and Garner, 1970; Gautier et al., 2010). Thereby, the point bar head is normally covered by a coarse material (e.g., Bridge and Jarvis, 1976; Bluck, 1982). During low discharges, however, deposition has been perceived to occur at the point bar head (Pyrce and Ashmore, 2005; Kasvi et al., 2013a). Concurrently, slower flow velocities, near bank inward flow, and flow convergence cause accretion of fine material over the point bar tail and margins (Bridge and Jarvis, 1976; Nelson and Smith, 1989; Pyrce and Ashmore, 2005; Clayton and Pitlick, 2007). However, coarse grains may roll and slide toward the pool, as the weak secondary flow cannot transport them (Bridge and

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[*] Corresponding author. Tel.: +358 504077293; fax: +358 2 333 5040.
E-mail address: elina.kasvi@utu.fi (E. Kasvi).

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Jarvis, 1976; Dietrich and Smith, 1984; Clayton and Pitlick, 2007). On the top of the point bar, coarse (e.g., McGowen and Garner, 1970; Kasvi et al., 2013b) and fine (e.g., Allen, 1964; Bluck, 1971; Bridge and Jarvis, 1976) materials can be found, depending on the flow conditions. The resulting spatial variation of the grain sizes and sorting of the bed sediment, in turn, affect the fluviomorphological processes (Dietrich and Smith, 1984). The sorting affects the incipient motion through hiding and exposure (e.g., Parker et al., 1982; Clayton, 2010). High sediment sorting has, for example, been noticed to increase the transport rate of fine particles and diminish the transport rate of coarse particles (Clayton, 2010). In a curved channel, the unequally distributed sorting of bed material may therefore lead to spatial variability in the flow conditions required to transport a certain size fraction.

As a consequence of the accretion of the point bar and erosion of the outer bank, convex and concave banks move outward, leading to bend deformation and development (e.g., Hickin, 1974). Meander development has been long thought to be exclusively bank erosion-driven (e.g., Hasegawa, 1989); however, recent studies suggest that the growth of a point bar can also force the outer bank to erode (the so-called *bar pull* process), which leads to channel migration (Eke et al., 2014). As the meander bend evolves, the bend curvature increases and the point bar grows laterally toward the outer bank (Hickin, 1974; Blanckaert, 2011). In mature bends with a high curvature, the shift of the HVC toward the outer bank is not as evident as in less-developed bends, and the secondary circulation may not form (Blanckaert, 2009).

Bends in different phases of development also experience different changes (Hickin, 1974; Hooke, 1977, 1995, 2003). In more mature bends with well-developed point bars, bedload transport across the bar decreases, transport along the channel thalweg increases, and sediment is deposited along the bar margin (Pyrce and Ashmore, 2005). The outer bank erosion and inner bank deposition also shift from downstream to upstream of the apex (Hickin, 1974; Hooke, 1995; Pyrce and Ashmore, 2005). This leads to increases in bend asymmetry.

The spatial and temporal patterns of the meander bend's fluviomorphology are complicated to study, as their variation is notable, which creates a great challenge in measurement. Field investigations on meandering streams have been carried out for decades (e.g., Bridge and Jarvis, 1976; Dietrich and Smith, 1979; Thompson, 1986) and new insights into the fluviomorphological processes on natural meandering streams have been gained continuously as the methods have developed (e.g., Frothingham and Rhoads, 2003; Gautier et al., 2010; Engel and Rhoads, 2012; Kasvi et al., 2013b). However, all of these studies suffer from either a lack of detailed geometric data owing to cross-sectional surveys or from poor temporal resolution of the flow-field data, or both.

During the twenty-first century, LiDAR (light detection and ranging) technologies have been replacing traditional methods in topographical surveys (Hohenthal et al., 2011; Lotsari et al., 2014a); additionally, computational fluid dynamics (CFD) has become a customary research approach in riverine studies, including meandering river environments (e.g., Lane et al., 1999; Booker et al., 2001; Rodriguez et al., 2004; Alho and Mäkinen, 2010; Motta et al., 2012; Kasvi et al., in press). The CFD can capture the variation in flow characteristics and sediment transport rate over a whole reach and whole flood event without disturbing the flow field. Also, the number of studies combining various approaches, such as field survey, remote sensing, CFD and laboratory tests, has been increasing continuously (e.g., Darby et al., 2002; Lane et al., 2007; Ottevanger et al., 2012; Lotsari et al., 2014b). These studies have shown that there are evident advantages in combined approaches, because a shortage in one approach may be overcome by another (Kleinhans, 2010). Yet, despite the extensive amount of research, the spatial and temporal patterns of fluviomorphological processes over meander bends and point bars are not yet fully understood.

Our aim is to study the spatial patterns of fluviomorphological processes over meander bends and point bars using a unique methodological approach that combines traditional field survey methods, close-range remote sensing, and computational fluid dynamics. We map the morphological changes using MLS (mobile laser scanning), TLS (terrestrial laser scanning), and echo sounding, as well as improve the interpretation of the fluvial formations over the point bars using a photomosaic acquired from an unmanned aerial vehicle (UAV). A two-dimensional hydrodynamic model with sediment transport provides spatially and temporally extensive information of the flow field and sediment transport. In the Results and discussion section, we combine and compare this study's results with the previous knowledge of meander bend fluviomorphology and discuss the feasibility of the used methodological approach in increasing the understanding of fluviomorphological processes of the meander bends.

2. Fluviomorphological background of the study area

The study was conducted in northern Finland on the sub-arctic, meandering Pulmanki River (Fig. 1A, B). The river channel has been eroded in the Pulmanki valley, where tens of metres of glaciofluvial material were deposited during the retreat of the continental ice (Mansikkaniemi and Mäki, 1990). The channel is mobile, and its banks are sensitive to erosion; the channel and point bars are devoid of vegetation. A snowmelt-induced spring flood occurs annually in May and is normally the only flood event of the year. The seasonal discharge ranges from 1.5 to 70 $m^3\ s^{-1}$. The meander point bars are only inundated during the spring flood. The sediment transport is dominated by a sandy bedload. The bed material is mainly sand, but grains up to 16 mm in diameter are transported as bedload.

This study focuses on the morphological changes and formations caused by the spring flood of 2013, during which the peak discharge (66.5 $m^3\ s^{-1}$) was exceptionally high but the water level did not rise as notably as the discharge (Fig. 1C, Table 1). The study reach of 1700 m consists of five meander bends, three of which are investigated in this study (Fig. 1B, Table 2). Bend 1, the most upstream bend, has erosion protection on the concave bank, while bends 2 and 3 are in their natural state: the steep concave banks are covered by berry springs and alpine birches (~2 m in height), which bind the erodible material. Each bend has a point bar (referred to as point bars 1, 2, and 3 according to the bend that is free of vegetation). Bend 1 is more mature compared to the other two bends (Brice, 1974; Hickin, 1974; Hooke, 1977, 1995). It has the largest channel width, sinuosity, and radius of curvature, as well as the largest point bar.

Extensive field measurement campaigns have been carried out in the study area since 2009 (Table 1). The spring flood-induced morphological changes and formations on the studied bends and point bars have shown remarkable annual variation (Kasvi et al., 2013b; Lotsari et al., 2014b; Table 1). The share of the net erosion over the point bars has been smaller the higher the spring-flood discharge has been (Lotsari et al., 2014b). Also, the duration of submergence for the point bars has inversely influenced the share of erosion in the total morphological changes over the point bars (Lotsari et al., 2014b). The locations of the erosion and deposition over the point bars have also varied significantly from year to year.

3. Material and methods

3.1. Traditional field data collection and close-range remote sensing

3.1.1. Topographical and bathymetrical surveys

The river geometry was measured before and after the spring flood of 2013. The pre-flood LiDAR survey was realised before the winter (September 2012). The TLS measurements were collected using a Faro Focus3D 120 with point spacing of 6 mm at a distance of 10 m from the scanner. Spherical reference targets were used to georeference the TLS data. In total, 5, 2, and 4 reference targets were placed on point bars 1, 2, and 3, respectively. The locations of each scan station and sphere were measured using RTK-GNSS (real-time kinematic global navigation satellite system). Subsequently, the scans were transformed