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Dynamic meandering in response to upstream perturbations and floodplain formation

F. Schuurman [a,b,*], Y. Shimizu [c], T. Iwasaki [d], M.G. Kleinhans [a]

[a] Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands
[b] Department of Rivers, Deltas and Coasts, Royal HaskoningDHV, Amersfoort, The Netherlands
[c] Laboratory of Hydraulic Research, Graduate School of Engineering, Hokkaido University, Sapporo, Japan
[d] Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, IL, USA

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ABSTRACT

River meandering results from spatially alternating bank erosion and bar growth. Recent flume experiments and theory suggest that a continuous inflow perturbation is a requirement for sustained meandering. Furthermore, flume experiments suggest that bar–floodplain conversion is an additional requirement. Here, we tested the effects of continuous inflow perturbation and bar–floodplain conversion on meander migration using three numerical morphodynamic models: a 1D-model, and two 2D-models with one of them using adaptive moving grid. We focused on the interaction between bars and bends that leads to meander initiation, and the effect of different methods to model bank erosion and floodplain accretion processes on meander migration. The results showed that inflow perturbations have large effects on meander dynamics of high-sinuosity channels, with strong excitation when the inflow is periodically perturbed. In contrast, inflow perturbations have rather small effect in low-sinuosity channels. Steady alternate bars alone are insufficient to cause high-sinuosity meandering. For high-sinuosity meandering, bar–floodplain conversion is required that prevents chute-cutoffs and enhances flow asymmetry, whilst meandering with chute-cutoffs requires merely weak floodplain formation, and braiding occurs without floodplain formation. Thus, this study demonstrated that both dynamic upstream inflow perturbation and bar–floodplain conversion are required for sustained high-sinuosity meandering.

1. Introduction

River meandering (Fig. 1) is a well-studied subject in fluvial morphology with a long history of literature about the cause, processes and prediction of meandering. Nevertheless, the cause or causes of meander initiation and the necessary conditions for sustained meander migration are still topics of debate. Below we briefly review the combination of factors that is thought to be conducive to meandering, in particular the formation of alternate bars, the formation of floodplains, bend-cutoffs and upstream perturbations of curvature.

In the past, alternate bars formed by intrinsic instability have been credited to cause meander bend initiation in straight channels (e.g. Parker, 1976). However, these bars commonly have wavelengths several times smaller than meanders and migrate too fast to initiate meandering (Olesen, 1983; Blondeaux and Seminara, 1985; Whiting and Dietrich, 1993), with evidence also in nature (Fig. 1d, e). In contrast, forced alternate bars, induced by a steady instability such as a groin, seepage or meander bend, are able to initiate meandering (e.g. Ikeda et al., 1981; Blondeaux and Seminara, 1985; Struiksma and Crosato, 1989; Hall, 2004; Crosato and Mosselman, 2009). Alternatively, initial channel curvature has been used to start meandering in flume experiments and modeling (e.g. Duan and Julien, 2005; Asahi et al., 2013). Sustained meander migration, however, requires a sustained dynamic perturbation on the upstream boundary, as found in highly simplified linearized meander migration modeling (Lanzoni and Seminara, 2006). Without a dynamic perturbation, a meandering channel would return to its original state without bends, similar to a propagating wave. This was partly confirmed by flume experiments of Van Dijk et al. (2012), who showed that meander migration rates gradually decline in case of a static inflow perturbation, whereas meander migration continues in case of a dynamic inflow perturbation. However, such flume experiments usually only have the length of a few meanders, which is perhaps too short to enable internal perturbations to emerge and drive further meandering. Furthermore, the question remains how far downstream the effect of upstream perturbation propagates, because the characteristic downstream distance of influence of a perturbation in a meandering river is relatively short (Struiksma et al., 1985). Also, linear analyses showed that a straight channel with erodible bed and turbulent flow is intrinsically unstable, which results in bars and bends without the need for an external forcing (Struiksma et al., 1985;

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* Corresponding author at: Department of Rivers, Deltas and Coasts, Royal HaskoningDHV, The Netherlands.
E-mail address: filip.schuurman@rhdhv.com (F. Schuurman).

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Fig. 1. Examples of a. high-sinuosity meandering river characterized by abundance of vegetation along the river, a lack of bars, and neck-cutoffs (Rio Purus, Brazil); b. low-sinuosity meandering river with low vegetation density and chute-cutoffs (Allier, France); c. meandering river with bars forced by channel curvature (Wabash River, USA); d. meander bend with free bars, including mid-channel bars (Rio Parnaiba, Brazil); e. low-sinuosity river with free alternate bars (Cross River, Nigeria); f. asymmetrical shape of the alternate bars with bar-tail limbs at the downstream (Indus River, Pakistan). Flow in all examples is from left to right.
Source: Bing Maps (c, d, f) and Google Earth (a, b, e).

Blondeaux and Seminara, 1985). Thus, here we test whether a dynamic perturbation is indeed required for sustained meander migration and cutoff dynamics, using a situation with sufficient length.

Another requirement for meandering is a single-threaded channel without mid-channel bars, a conditions met within a limited range of relatively low width-depth ratios (e.g. Engelund and Skovgaard, 1973; Fredsoe, 1978; Crosato and Mosselman, 2009; Kleinhans and Van den Berg, 2011). The width-depth ratio in meandering rivers depends on the balance between bank erosion and inner bend accretion rates. Many meandering rivers have rather constant and uniform channel widths even though the channel migrates (Parker et al., 2011). This implies a dynamic equilibrium between bank erosion and bar growth in the inner bend, called 'bank pull' and 'bar push' by Parker et al. (2011), Eke et al. (2014) and Van de Lageweg et al. (2014), exists, despite bank erosion and bar growth have different underlying processes. It might justify the application of constant and uniform channel width in the classical one-dimensional meander migration models of Ikeda et al. (1981), Howard and Knutson (1984), Parker and Andrews (1986), Crosato (1987), Johannesson and Parker (1989) and Sun et al. (1996). However, recent modeling and flume experiments demonstrated that equilibrium channel width is only achieved by additional processes to reduce bank erosion rates or increase inner bend accretion rates (Dulal et al., 2010; Parker et al., 2011; Van Dijk et al., 2013b). Acceleration of inner bend accretion is, for example, achieved by vegetation encroachment to convert the inner bend bars into floodplain (Gran and Paola, 2001; Erskine et al., 2009; Tal and Paola, 2010; Erskine et al., 2011; Van Dijk et al., 2013a; Iwasaki et al., 2015), Fig. 1b), hereafter called 'bar–floodplain conversion'.

Numerical two-dimensional morphodynamic meander models have been using a variety of methods to compute bank erosion and bar–floodplain conversion (e.g. Mosselman, 1995; Parker et al., 2011; Asahi et al., 2013; Nicholas, 2013). Despite their large differences, most of these models were able to produce high-sinuosity meandering with nearly uniform and constant channel width. However, many two-dimensional meander models have been applied on laboratory scale. The bar–floodplain conversion rules in these models ignored time scale differences between bed evolution (i.e. sand transport, bar dynamics) and bar–floodplain conversion (i.e. vegetation encroachment, deposition of fine cohesive sediment on the pointbars). This would render these models useless for 'real world' rivers.

Bend-cutoffs are well-known to be critical aspects of meander dynamics, with neck-cutoffs reducing the sinuosity of high-sinuosity meanders (Fig. 1a, c; e.g. Hooke, 2004; Camporeale et al., 2008). Chute-cutoffs in high-sinuosity rivers result in a minor decrease of sinuosity (Grenfell et al., 2014), but in low-sinuosity channels, they may prevent high-sinuosity (Fig. 1f; Howard, 1996; Constantine et al., 2010) and lead to potential braiding (Fig. 1b; Sarker and Basumallick, 1968; Grenfell et al., 2012; Van Dijk et al., 2012). Most numerical meander migration models can model either neck-cutoffs or chute-cutoffs, but not both. This is, among others, because of a dynamic boundary-fitted grid, which automatically removes the inner bend bars from the computational domain and thus disable chute-cutoffs, or because the model assumes a simplified transverse bed profile. At the same time, models without boundary-fitted grid might overestimate channel widening and chute-cutoffs. A solution is application of different models for the same case to investigate meander dynamics.

The objective of this chapter is to determine the necessary and sufficient conditions for meander initiation and sustained meander migration. In order to accomplish this objective, we a) determined the effect of inflow perturbations on meander initiation and meander dynamics, i.e. growth, migration and cutoff, b) analyzed the interaction between bed deformation (bars) and channel deformation (meander bends), and c) determined the contribution of bank erosion and bar–floodplain conversion to meander dynamics. We conducted simulations with two