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Biomorphodynamic modelling of inner bank advance in migrating meander bends

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ABSTRACT

We propose a bio-morphodynamic model at bend cross-sectional scale for the lateral migration of river meander bends, where the two banks can migrate separately as a result of the mutual interaction between river flow, sediments and riparian vegetation, particularly at the interface between the permanently wet channel and the advancing floodplain. The model combines a non-linear analytical model for the morphodynamic evolution of the channel bed, a quasi-1D model to account for flow unsteadiness, and an ecological model describing riparian vegetation dynamics. Simplified closures are included to estimate the feedbacks among vegetation, hydrodynamics and sediment transport, which affect the morphology of the river-floodplain system. Model tests reveal the fundamental role of riparian plants in generating bio-morphological patterns at the advancing floodplain margin. Importantly, they provide insight into the biophysical controls of the 'bar push' mechanism and into its role in the lateral migration of meander bends and in the temporal variations of the active channel width.

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1. Introduction

It has long been recognised that meander bends migrate laterally as a result of a curvature-forced flow pattern that causes erosion of the outer, concave bank and deposition of sediment at the inner, convex bank [44,67]. Most river meandering modelling has been based on the solution of the physical laws for momentum and mass conservation for water flow over a movable bed (e.g. [5,39,40,46,77]). However, in addition to flow and sediment dynamics, the contribution of vegetation to channel morphodynamics is becoming increasingly recognised (e.g. [14,16]). In this context, certain key plant species act as physical 'ecosystem engineers', interacting with flow and sediment processes to drive channel morphological changes [27,33], and in some cases to induce a topographic signature of vegetation on river channel form [3]. In the case of meandering rivers, the progressive deposition of sediment, in the form of a point bar, at the convex bank is often associated with the development of a corrugated floodplain surface, characterized by a succession of ridges and swales. These ridge-swale forms represent a succession of features, which originated as *meander scrolls* or *scroll bars* (e.g. Fig. 1) deposited in association with point bar development and then progressively incorporated into the floodplain as the meander migrates [34,35,52,54]. Field observations have revealed that scroll bars are often cored and stabilised by woody and other vegetative material (e.g. [53]). In some cases this vegetative material sprouts to form a riparian shrub cover that further enhances local sediment retention and ridge/scroll development [29,49,57].

These mutual feedbacks among flow, sediment and riparian vegetation dynamics in evolving meander bends can be viewed as a series of interacting 'unit processes' that control bank dynamics, sediment retention and the initiation of characteristic vegetated pioneer landforms. The reinforcing action of roots stabilizes bank sediments increasing bank resistance to erosion processes, thus affecting the migration rates of the inner and outer banks of meander bends and inducing morphological changes at both local (cross-section) and reach scales [1,7]. Over-bank deposition is particularly relevant in the aggradation processes of meander inner banks [34] and decreases with distance from the river edge, partly because, in vegetated floodplains, the drag resistance of mature trees is lower than that of early-stage bushy growth forms [49].

Such complex dynamics are fundamentally related to the natural variability of river flows, both because of the direct action of flow on channel morphodynamics and also because of indirect impacts on riparian vegetation evolution. In particular, very high flows determine channel widening through net bank erosion, while an absence of very high flows allows width contraction through vegetation growth and aggradation of scrolls at the convex bank. At a decadal scale, the imbalance between the rate of cutbank erosion and point-bar accretion has been observed to lead to a *concertina-like* movement

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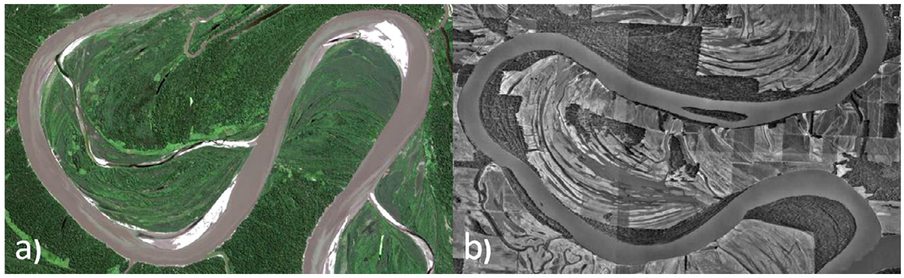

Fig. 1. Example of scroll formations at the inner bank of evolving meanders within vegetated floodplains, suggesting the contemporary presence of patterns in vegetation distribution and in the floodplain topography. (a) Rio Ucayali, Peru and (b) Wabash River, close to the Kentucky border, USA from an historical image.
Source: Google Earth.

of the channel with the cutbank retreating and then pausing, and the convex bank advancing to 'catch up' [53,55]. This discontinuous process has been linked with fluvial processes at the scale of the overall river planform (e.g. [36,37]) but has been represented as a continuous process in classical meander morphodynamic models, which implicitly assume that the two opposite banks move at the same rate so that the channel width is constant in time [8,17,24,38,80].

The structure of riparian tree communities is also strongly influenced by the hydrological regime through the processes of flow disturbance and moisture supply to the vegetation. The temporal distribution of free surface elevation influences the delivery of seeds and vegetative propagules to recruitment sites, the moisture conditions and disturbance exposure at those sites, and thus potential recruitment success (e.g. [47]). Free surface variations also influence groundwater levels in the alluvial aquifer and thus the availability of moisture to support plant survival and growth (e.g. [28,60]). During floods, flow may reduce vegetation coverage by eroding, undermining or uprooting vegetated areas, particularly on the outer bank, and also by burying vegetation, particularly on the inner bank [18,58]. During the subsequent low flow stages, buried vegetation may sprout through newly deposited sediments on the point bar and new plants may germinate from the newly-deposited sediment. Plants can also colonize the exposed sediments of the point bar at the inner bank following propagule dispersal by water during flow pulses or by other agents, particularly wind [31,32]. As a result, vegetation structure and distribution within the riparian corridor reflects the rate of river migration and proximity to the river edge, local topography and hydrological conditions [49,61–64]. Furthermore, the presence of a hotspot of physical ecosystem engineering by plants occurs on the inner bank as the development of scroll bars and extension of the floodplain is strongly influenced by the rapid growth of particular disturbance-tolerant plant species [27,29].

Despite recent quantitative advances provided by flume experiments [7], the above processes and dynamics are quite well known from a conceptual and qualitative viewpoint, mainly related to field observations of particular river systems. However, with a few notable exceptions (e.g. [61,62]), there has been little attempt to incorporate these vegetation-related processes into modelling approaches to simulate river meandering morphodynamics.

Modelling research in meander morphodynamics is traditionally based on a unified, time-averaged parameterization of the markedly distinct processes occurring at the advancing and cutting banks [39,46], even when accounting for the active role of riparian vegetation [61,62] or floodplain spatial heterogeneities [26]. This knowledge gap has prevented the advancement of understanding of the key controls on floodplain pattern development, including the evolution of scroll bars and temporal adjustments in the channel width of evolving meander bends. Such issues have implications for broader questions concerning the conditions that may favour the systematic presence of chute cutoffs on some meandering rivers [25], and the geomorphological transitions from single-thread to multi-thread meandering channels [42,78].

Only recently have modelling efforts addressed the separate dynamics of each river bank, although with some bias towards the eroding bank, and floodplain-channel interactions. Following the novel approach of Parker et al. [58], Eke et al. [22] have modelled the planform evolution of river meanders by introducing separate closure relations for the migration of the advancing and the retreating banks. Together with recent experimental work [74] they predict how channel width adjusts through time in response to a dynamic 'dialogue' between the two banks, raising the question of whether width adjustments and channel migration are mostly supported by a 'bar push' or a 'bank pull' process. These decoupled bank relations account for the sediment exchange between the two bank regions and the channel region, but they lack an explicit description of the underlying biophysical processes of flow-sediment-vegetation interactions.

In this paper, we develop a bio-morphodynamic model that is able to predict, albeit in a simplified way, the mutual interaction between flow, channel-floodplain morphodynamics and riparian vegetation dynamics in evolving meander bends. We also explore the model outcomes:

1) to gain a quantitative insight into the dynamics of inner bank advance and its potential 'bar push' role in lateral bend migration;
2) to detect possible hydrological and vegetation controls on the temporal adjustments of channel width and on the development of topographic and vegetation patterns in the accreting floodplain region at the inner bank.

The model couples a minimalist approach for the interaction between riparian vegetation and river processes with a non-linear analytical model for the morphodynamics of a meander bend. Our approach represents one of the first attempts to develop a biophysically-based model for the advance of the inner bank of meander bends.

2. Methods

In order to achieve the objectives listed above, the bio-morphodynamic model incorporates the lowest possible level of complexity and, in its first stage of development, the interactions between the ecological system and flow dynamics have been investigated at the cross-section scale.

2.1. Modelling strategy and notations

The proposed model reproduces a suite of biophysical 'unit' processes through an algorithm that links representative sub-models for each unit process. Before providing a detailed description of each of these sub-models, a broad overview of the adopted modelling strategy is presented.

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