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Modelling autogenic morphodynamic processes in meandering rivers with spatial width variations

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Abstract. Most morphodynamic models of river meandering assume spatially constant width; depending on the intensity of spatial width variations, different meandering styles actually exist, often associated with mid-channel bars and islands. When intense enough, width oscillations characterize transitional planforms between meandering and braiding. We investigate, on a modelling basis, morphodynamic feedbacks between spatial curvature and width oscillations in river meanders, and related bedform patterns. Our review of existing mathematical models suggests that width-curvature interactions can be comprehensively analyzed by a hierarchy of models that descend from a two-parameters perturbation solution of the governing depth-averaged morphodynamic model. The focus is on in-stream, autogenic hydro-morphodynamic processes, and not explicitly on bank processes. Curvature-width interactions are fundamentally nonlinear: the perturbation approach allows to investigate the key effects at the first nonlinear interaction. In meanders with initially constant width, curvature nonlinearly forces mid-channel bar growth, promoting symmetrical bank erosion further downstream, possibly triggering width oscillations. These in turn can significantly affect the process of bend stability and therefore condition the curvature dynamics. Wider-at-bends meanders develop shorter bends and are morphologically more active compared to equiwidth meanders, coherently with the few available field observations. River evolution models aiming to separately simulate bank erosion and accretion processes shall incorporate these autogenic flow-bed nonlinearities. Because of its focus on meandering morphologies close to the tran-

sition with braiding, the proposed approach can be taken as a novel, physically based viewpoint to the long-debated subject of channel pattern selection.

1. Introduction

Alluvial channel patterns are known to form a continuum between the poles of single-thread meandering and multi-thread braiding (Figure 1). Although investigations on their controlling factors date back to the nineteenth century (*Lokhtin* [1897]), the topic still represents one of the fundamental open issues in fluvial geomorphology and morphodynamics. A huge amount of studies on river channel pattern and their environmental controls have been proposed in the last fifty years. They differ in aim and approach and are either qualitative or quantitative. Qualitative descriptive classifications (*Brice* [1982], *Mosley* [1987]) distinguish morphological types on the basis of morphometric indicators. Process-based qualitative classifications (*Schumm* [1977], *Church* [1992]), place more emphasis on the main reasons for a river to develop the observed morphology. Quantitative channel pattern predictors are of two major types. Discriminant functions separating conditions of occurrence of straight, meandering, braiding and in some cases anastomosing rivers have been both empirically (*Leopold and Wolman* [1957], *Ferguson* [1987] *Kleinhans and van den Berg* [2011]) and rationally (e.g. *Huang et al.* [2004], *Eaton et al.* [2010]) derived. Quantitative predictors based on migrating or steady bar theories in straight channels (*Callander* [1969], *Engelund and Skovgaard* [1973], *Parker* [1976], *Fredsœ* [1978], *Crosato and Mosselman* [2009]) predict channel pattern based on the linear solution of the depth-averaged equations that govern the hydro-morphodynamics of open channel flow.

An overview of the existing approaches indicates at least three main areas with great potential for scientific improvement. First, despite recent attempts at direct comparison [*Kleinhans and van den Berg*, 2011], the different approaches have seldom been explicitly linked one another, and their integration is recognized to have great potential for improved insight and predictive ability [*Eaton et al.*, 2010]. Second, most channel pattern classifications and prediction models tend to sharply discriminate between different river morphologies, although in practice the continuum of river patterns does not exhibit sharp thresholds [*Ferguson*, 1987]. A broad spectrum of intermediate or transitional morphologies (Figure 1b,c) indeed present typical features of both "pure" meandering, e.g. sinuosity (Figure 1a) and braiding, e.g. the presence of islands and the locally associated multi-thread tendency (Figure 1D). Third, the physics behind existing approaches is often relatively basic, particularly if compared with state-of-art morphodynamic modelling, through which reproduction of many complex and nonlinear morphodynamic processes has been achieved [*Seminara*, 2006].

The present paper focusses on river morphologies that can be considered intermediate between single-and multiple-thread, at the meandering-braiding transition, with the primary aim to quantify key morphodynamic processes occurring in these transitional patterns. It also presents a novel viewpoint on the channel pattern debate through a physically-based, nonlinear modelling approach which is combined with a descriptive channel pattern classification.

The paper builds on two basic assumptions. First, transitional morphologies can be viewed as a tendency of single-thread meandering rivers to develop some degree of multi-channel behavior. Therefore, insight in related morphodynamic processes can provide complementary viewpoints to understand differences among channel patterns. Besides being an intuitive concept, this is also suggested by the recent study of *Kleinhans and van den Berg* [2011], who distinguish meandering rivers according to the dominant occurrence of "scroll bars" or "chute bars". Chute bars and chute cutoffs are associated with more pronounced spatial width variations and tend to plot close to the meandering/braiding discriminator curve at relatively high stream power (Figure 5 in *Kleinhans and van den Berg* [2011]).

The second, related assumption is that the planform geometry of meandering and transitional river styles can be described through their spatial curvature and width distributions, with the amplitude of width oscillations increasing for transitional morphologies. This emerges from descriptive channel pattern classifications. The one originally developed by *Brice* [1975] and lately refined by *Lagasse et al.* [2004] is particularly useful for this purpose, because it essentially discriminates different styles of meandering based on the intensity of spatial width oscillations. In Figure 2 we have reordered meandering styles categories (A,...G) according to the absence / presence of spatial variations in channel width. It clearly appears that styles of alluvial meandering differ for the degree and character of channel width and curvature variations, with transitional forms having the highest degree of width oscillations. Figure 2 suggests that channel width may vary rather systematically along a meander wavelength for *wider-at-bend* streams (classes B_2, C, D, G_2) and more irregularly for class E streams. Therefore, the spatial width distribution can be expected to play a key dynamic role in analogy with that of channel curvature in equiwidth meanders.

A mechanistic understanding of the morphodynamics of transitional patterns requires to investigate which physical processes control the presence of more or less pronounced spatial variations in width. A nearly obvious consideration is that the width oscillations are produced when point-bar growth and associated inner-bank advance cannot keep up with outer-bank erosion [*Nanson and Hickin*, 1983].

A complementary and relatively unexplored argument is to which extent the spatial oscillations in width may be significantly controlled by in-stream (or "autogenic") morphodynamic processes, i.e. those controlling the bed-flow pattern in the central flow region, where sidewalls boundary effects can be ignored. Field evidence has indeed been provided [*Richards*, 1976] that systematic spatial variations of channel width can develop in the absence of spatial variations in bank material composition and in close association with central bars diverting the flow against the banks. This suggests that, besides near-bank dynamics, autogenic hydromorphodynamic processes may significantly control the planform and bedform evolution.

Moreover linear models based on autogenic, curvature-related hydromorphodynamic processes in equiwidth meanders, and only very roughly accounting for bank processes, have correctly reproduced key features of meander dynamics (e.g. *Ikeda et al.* [1981], *Blondeaux and Seminara* [1985], *Struiksma et al.* [1985], *Odgaard* [1986], *Howard* [1992], *Camporeale et al.* [2007]). Significant insight can therefore be expected from the investigation of autogenic processes associated with the contemporary presence of channel curvature and width variations that describe the observed variety of meandering styles and intermediate patterns.

The paper addresses this second argument and to this aim it focusses on the following specific research questions. (1) Which physical processes are associated with transitional meandering styles? (2) Which cause-effect relationships are associated with the contemporary presence of spatial curvature and width variations? (3) To which extent morphological differences between equiwidth and transitional meandering styles can be investigated through physics based instream morphodynamic models?

Answers to the above questions are explored first by reviewing the present state of art about the role of curvature and width variations in single-thread rivers, with focus on both field observations and mathematical modelling (Section 2). Some of these models can be hierarchically derived within the same unified mathematical framework, with the advantage that models at each order of approximation can be associated with a specific physical process, thus fitting the purpose of the present review. The key parameters used to quantify the degree and character of curvature and width variations are introduced in Section 3 and quantified referring to field cases. Section 4 presents the unified hierarchical framework of depth-averaged morphodynamic models for the flow-bed topography in a meandering channel with spatial width variations. The solution approach is based on a two-parameters perturbation expansion. Sections 5, 6 and 7 illustrate possible answers to the specific research questions. Finally, results are harmonized and put in a broader perspective in the concluding Section, which also summarizes open issues for future research.

2. State of Art

Relatively few investigations have explicitly investigated the planform geometry, bedform characteristics and the morphodynamic processes typical of meandering channels with spatial width variations. In the following the most relevant indications for the present work, emerging from field observations and from mathematical modelling, are separately reviewed.

2.1. Field Observations

Information about the causes for development and the dynamic role of width variations in natural meandering rivers can be drawn from two major types of studies. First, analysis of the large available meander bend dataset compiled by *Lagasse et al.* [2004] on the basis of *Brice* [1982] original database provides quantitative evidence of morphodynamic differences between meandering rivers that significantly differ in the degree of spatial width oscillations. Second, a series of reach-scale field investigations (*Knighton* [1972], *Richards* [1976], *Hooke* [1986], *Hooke and Yorke* [2011]) have documented key dynamic interactions among mid-channel bars (bedforms) and channel width oscillations (planform) that have occurred at the time scale of few channel-forming events in selected meandering river reaches.

Data on hundreds of bends on 89 different meandering rivers in the U.S. are reported in *Lagasse et al.* [2004]'s dataset, and are grouped according to the updated Brice meandering river pattern classification (Figure 2). A relatively simple analysis of planform geometry and migration properties of constant width meander bends (class B_1) and wider-at-bends meandering reaches (class C) reveals that the observable geometrical discrepancies between the two classes might actually reflect differences in the controlling morphodynamic processes. Wider-at-bends meandering reaches show a higher degree of morphological activity with respect to those with constant width, as already argued by *Brice* [1982] (Figure 3a). For instance annual bend apex movement ζ^* exceeding 2% of the reach-averaged channel width W^* can be measured in nearly 50 % of the analyzed wider-at-bends reaches and only in 20% of the constant-width meander bends. The apex movement ζ^* has been defined as in *Lagasse et al.* [2004]: a combination of extension, translation and expansion of a meander loop.

Figure 3b (adapted from *Luchi et al.* [2011]) shows the cumulative frequency distributions of meander wavelength L^* scaled by the reach-averaged channel width W^* for the two meandering styles C and B_1. More than 60% of the constant width meanders' wavelength exceed 15 times channel width, while only less than 40% of the wider-at-bends do. As selection of different meander wavelengths is determined by different balances between competing morphodynamic processes (e.g. *BollaPittaluga et al.* [2009]), this also suggests that the two styles of meandering may reflect different autogenic physics.

More insight on the physics of meandering channels with spatial width variations is provided by field investigations carried out at the meander wavelength scale, complementing the general tendencies illustrated in Figure 3. Width variations along meander bends are often associated with mid-channel bars and vegetated islands (Figure 1b,c). The observed morphology may represent a snapshot along a time sequence whereby the stream may cut through and eventually abandon one of the low-flow branches [*Hooke and Yorke*, 2011]. Central bars and local widening not necessarily develop at bend apexes but can be observed near inflection points (Figure 1C). Characteristic cycles of development of mid-channel bars and longitudinal widening-narrowing sequences in single-thread streams have been documented in the field by *Knighton* [1972], *Richards* [1976], *Hooke* [1986] and *Hooke and Yorke* [2011] while other studies mainly focussed on single anabranches of braided rivers (e.g. *Ashworth* [1996], *Klaassen et al.* [1993]), where the bed and banks evolve at more comparable timescales [*Bertoldi and Tubino*, 2005].

Knighton [1972] described the time development of a mid-channel bar in the River Dean (UK). The bar originally developed in a meander inflection region between two consecutive bends in correspondence of cross sectional overwidening related to bank erosion. A two-channel pattern was observable at low flows, when the bar emerged and turned into a temporary island (*Knighton* [1972], Figure 1). A sequence of competent flood events caused a shift in the flow partition between the two branches, causing a temporary multichannel behavior in what is normally classified as a meandering river.

A detailed description of the characteristic timescales and cycles of development of mid-channel bars in a large number of bends of the River Dane (UK) has been provided by *Hooke* [1986] and *Hooke and Yorke* [2011]. *Hooke* [1986] observed a typical sequence whereby mid-channel bars started forming close to riffles, then related to cross-sectional overwidening and after some formative events became attached to one of the banks. This typical sequence has been lately confirmed by *Hooke and Yorke* [2011] in the same River Dane (UK) having a characteristic timescale of few channel forming events (7-10 years). Mid-channel bars position relative to bend apexes display a large scatter among different bends, in most cases not coinciding with the bend apex.

The reach-scale observations of *Knighton* [1972] and *Hooke* [1986] confirm the detected tendency of higher channel mobility and rapid bank erosion to occur in reaches with more pronounced local widening. Also these observations confirm that the spatial width oscillations are cyclic in time, reflecting a correlation with bed patterns oscillations. The associated dynamics of mid channel bars contribute to the planform evolution of the most active bends. Mid-channel bar growth followed by attachment to the inner bank promotes bend growth due to the progressive abandonment of the inner branch [*Hooke*, 1986]. When the opposite behavior applies, the flow concentrates into the inner channel and reproduces an analogous dynamics to that of chute cutoffs occurring across braid bars in multi-thread rivers [*Ferguson et al.*, 1992] and limits the increase of sinuosity. Although cross-sectional overwidening has been identified as the primary mechanism responsible for the presence and development of mid-channel bars (*Knighton* [1972], *Hooke* [1986]), however still it is not clear whether bank erosion has a forcing or following function (*Lewin* [1981]) or to which degree bed and banks interact dynamically through a mutual feedback process (*Bertoldi and Tubino* [2005]).

Overall, the available field observations suggest significant dynamic differences between equiwidth and transitional meandering morphologies, provide wavelength-scale description of key physical processes and suggest that autogenic - or instream - processes occurring in the central flow region can exert a significant control on the observed morphologies. However a clear detection of cause-effect relationships between the competing mechanisms and the establishment of a clearer legacy with meandering pattern descriptors requires a comprehensive theoretical framework that still needs to be developed.

2.2. Mathematical Modelling

Several types of mathematical models suitable to investigate morphodynamic processes in meandering rivers with spatial width variations have been developed in the past two decades. The focus and approaches of these models differ significantly. A first distinction can be made on the basis of the method used to compute the flow and bed topography fields: both analytical and numerical solutions of the shallow water and sediment transport equations have been proposed, as well as reduced complexity models. A second distinction can be made between models incorporating in detail the physics of bank processes and those incorporating them only indirectly through a linear, Partheniades-type relationship between the lateral channel migration rate and the near-bank excess longitudinal velocity or shear stress (*Partheniades and Paaswell* [1970], *Ikeda et al.* [1981]). Based on this, we suggest to group existing models into four categories as reported in Table 1.

Since decades, most modelling-based physical insight on river meandering has been obtained by means of simplified analytical solutions of morphodynamic models obtained through perturbation methods [*Holmes*, 1995]. These approaches provide the foundation for all models in categories 1 and 2 of Table 1. The well known bend theory originally proposed by *Ikeda et al.* [1981], *Hasegawa* [1977], is obtained by linearizing the equations governing flow, sediment transport and the planform evolution. Among the major achievements, the original bend theory and its subsequent refinements have allowed predicting the characteristic spatial scales of developing meanders [*Edwards and Smith*, 2002; *Frascati and Lanzoni*, 2009], understanding conditions under which a meander can grow towards mature loops [*Parker et al.*, 1983; *Blondeaux and Seminara*, 1985]; reproducing typical meander loop migration rates [*Crosato*, 2009] and shapes [*Seminara et al.*, 2001; *Zolezzi et al.*, 2009]; investigating the nature of meander instability [*Lanzoni and Seminara*, 2006]; distinguishing stable and unstable bends in field cases [*Luchi et al.*, 2007]; and the dominant direction of upstream/downstream 2D morphodynamic influence [*Struiksma et al.*, 1985; *Zolezzi and Seminara*, 2001; *Zolezzi et al.*, 2005]. When coupled with planform evolution models at larger time scales, long-term simulation of of meander floodplain development [*Howard*, 1992; *Sun et al.*, 1996] and assessment of possible existence of chaotic behaviors [*Stolum*, 1996; *Frascati and Lanzoni*, 2010] have been also achieved.

The rationale behind the application of perturbation methods is that flow and bed topography deformation in curved channels can be assumed to be small with respect to the flow velocity and water depth that would occur in a straight channel with flat bed fed by the same discharge and with the same slope, width and sediment size. This is theoretically justified because curvature is typically a small parameter - channel radius of curvature is much larger than reach-averaged width - and planform geometry is slowly varying in many meander bends. Most models used to study bend stability and meander planform evolution are therefore linear [*Odgaard*, 1986; *Johannesson and Parker*, 1989; *Crosato*, 2008], the perturbation expansion being truncated at the first order of approximation. The effect of flow nonlinearities has been studied by *Seminara and Tubino* [1992] who extended the analysis at the third order of the perturbation expansion. *Seminara and Solari* [1998], lately extended by *BollaPittaluga et al.* [2009] developed a slightly modified perturbation approach that relaxed the assumption of small amplitude flow and bed perturbations thus allowing a more complete treatment of nonlinear effects. *Tubino and Seminara* [1990] modelled the conditions under which the migration of free bars is ceased in channels with variable curvature.

Planform evolution models of river meandering relate a representative near-bank shear stress or excess velocity to the lateral channel migration rate. Nearly all these models assume the river width to keep constant in space and time, imposing that the bank retreat rate is equal to the bank advance rate. This has been justified as a long term requirement for meandering rivers and has received some support (*Pizzuto and Meckelnburg* [1989]) from field observations on rivers with fairly uniform cohesive banks. The assumption of constant width has been relaxed only quite recently. Considering the significant scientific improvement obtained through meander models with constant width, it can be expected that allowing the presence of spatial width oscillations within a similar modelling framework can lead to improved insight of the morphodynamics of transitional morphologies.

The linear analysis of *Repetto et al.* [2002] focussed on the steady flow-bed topography deformation in straight channels with regular width oscillations, giving rise to mid-channel bars and potential braiding initiation when planform instability occurs. *Repetto and Tubino* [1999] investigated the nonlinear interaction between free migrating bars and steady central bars in the same planform configuration. In the case of curved channels, *Luchi et al.* [2010b] have modelled the linear and nonlinear development of mid-channel bars in meandering channels, which are typical features of transitional morphologies between meandering and braiding; *Frascati and Lanzoni* [2011] have extended the theory of *Repetto et al.* [2002] to channels with arbitrarily varying width, and applied this to meandering streams; *Luchi et al.* [2011] have analyzed the dynamic effect of spatial width oscillations on the process of meander bend stability; *Luchi et al.* [2012] have extended the nonlinear model of *BollaPittaluga et al.* [2009] to meanders with spatial width oscillations. Linear models for equiwidth meandering channels [*Camporeale et al.*, 2007] together with these more recent analytical theories for meanders with spatial width variations separately address the key physical processes emerging from the overview of field investigations (Section 2.1).

The present review aims to show that these models can be derived within a unified, hierarchical mathematical framework and that the resulting theoretical picture provides a quantitative physical insight on transitional morphologies. Moreover, because these models predict long term, "dynamic equilibrium" system tendencies, they are particularly suitable to be conceptually linked with descriptive channel pattern classifications, with a particular focus on the different styles of meandering. This will be presented in the next sections, together with some unpublished data and novel applications, to attempt a first answer to the research questions posed in the introduction.

Many other models can produce spatial variations in width, although the difference in scales of application, methods used for the mathematical solution and specific focus make them less suitable to be included within a hierarchical mathematical framework. Nevertheless, highlighting their key properties is needed in the present review to provide an overall modelling picture for transitional river morphologies.

Category (2) in Table 1 includes the approaches of *Chen and Duan* [2006], *Parker et al.* [2011], *Motta et al.* [2012] and *Eke and Parker* [2011], which represent the most promising and recent attempts to couple instream morphodynamics with a detail physical description of the dynamics of bank regions. Their outcomes cannot be considered as fully consolidated yet; therefore they will be discussed in the concluding section in relation to the open research perspectives.

Widening in meandering channels has been also simulated by a series of numerical models that couple two-dimensional, depth-averaged models of flow and bed topography in movable computational grids with process-based bank erosion models. These have been grouped under category (3) in Table 1 (e.g. *Mosselman* [1998], *Nagata et al.* [2000], *Darby et al.* [2002] *Jang and Shimizu* [2005], *Rüther and Olsen* [2007]). The algorithms have been written both in boundary-fitted non-orthogonal coordinate systems (following *Mosselman* [1991]) and on unstructured meshes [*Rüther and Olsen*, 2007], who used a 3D CFD approach. Models within this category can reproduce local widening in meandering rivers and mainly differ for the level of detail at which the physical processes causing bank erosion are incorporated and coupled with the flow-bed evolution model. For instance *Duan and Julien* [2005] separate the calculation of bank erosion from the advance of bank lines, using the parallel bank failure model for non-cohesive bank material and solving the near-bank mass conservation equation. *Darby et al.* [2002] consider the deposition of failed bank material at the toe of the bank and its subsequent removal. They show that the lateral sediment input due to bank collapse might lead to the development of a wider, shallower cross-section with respect to channels with fixed banks.

A common gap for the investigation of spatial width variations in meanders is the absence of a sound formulation for bank accretion, which is essentially accounted for as point bar deposition. Adequate modelling of bank accretion represents one of the major unsolved issues in river morphodynamic modelling [*Mosselman*, 2011] and is almost absent in all models belonging to the four categories of Table 1. An interesting attempt to explicitly model bank accretion has been made by *Coulthard and Wiel* [2006] when simulating the planform evolution of river meanders through the CAESAR model based on cellular automata. Although the physics of bank erosion and accretion in *Coulthard and Wiel* [2006] is strongly simplified - as for the flow and bed erosion/deposition model - the two banks processes are decoupled and separately described. Lateral bank erosion is computed as proportional to local channel curvature, derived on a cell by cell basis; bank accretion is simulated through two slightly different relationships for the lateral sediment exchange between the eroding and the accreting bank. Although the methods haven't been tested in detail, they are both based on the critical role played by the lateral exchange of sediments between the river and its floodplain for the spatial and temporal evolution of channel curvature and width. Such exchange in meandering rivers is intrinsically related to the process of spatially variable width adjustment: meander geometry itself implies that more sediment is eroded at the outside edge than can be deposited on the inside, as pointed out by *Lauer and Parker* [2008]. The meandering channel simulated by *Coulthard and Wiel* [2006] is wider-at-bends, with sharper bends tending to become wider. To the Authors' knowledge the work of *Coulthard and Wiel* [2006] is, strictly speaking, the only example of reduced-complexity model applied to simulate the planform evolution of river meandering with spatially variable width. In a broader sense, *Jagers* [2003], building also on *Klaassen et al.* [1993], proposed an object-based simulation model - "branches model" - for the planform evolution of braided streams, which also reproduced the planform evolution of the weakly meandering anabranches of the braided network. The two approaches of *Jagers* [2003] and of *Coulthard and Wiel* [2006] are grouped within reduced-complexity models - category (4) - in Table 1.

3. Quantification of Width and Curvature Variations in Meanders

The modelling focus of the present paper requires a quantitative knowledge of the properties of the spatial series of curvature and width variations. A considerable amount of studies has been devoted to the definition and analysis of the channel axis curvature and of its longitudinal variations since decades (e.g. *Kinoshita* [1961], *Ferguson* [1973]) and methods for computations based on aerial and remotely sensed images are continuously being improved (*Güneralp and Rhoads* [2008]). The same does not apply to width variations in meandering rivers, on which very few quantitative studies have been concentrated so far.

Most available data refer to reach-averaged values of channel width, for instance from hydraulic geometry studies that provide bulk relationships but do not capture the spatial fluctuations of width at the meander wavelength scale. The definition itself of meander width is not obvious. Computation of width from aerial images can pose problems of subjective interpretation that may prevent obtaining significant information in some cases. Direct field estimates of bankfull conditions can also show some degree of subjectivity where riparian areas are mainly grassland or covered with sparse plants especially close to gently sloping convex banks. *Luchi et al.* [2010a] recently proposed a more objective approach based on the application of non-uniform 1D steady flow model with fixed bed that can be used when bed topography data are known with enough detail.

A look at the planform of free meandering streams suggests two useful assumptions for morphodynamic modelling purposes. First, curvature and width are typically oscillating functions of the river arclength. Several reaches in alluvial river meanders typically display periodic planform sequences whereby the channel axis can be locally described by a sine-generated curve (*Langbein and Leopold* [1964]), a line whose curvature varies sinusoidally as a function of the arclength. These forms can develop towards fattened and skewed shapes or to compound loops (*Brice* [1974], *Hooke and Harvey* [1983]) that may be reproduced through the inclusion of odd higher harmonics (*Kinoshita* [1961], *Zolezzi et al.* [2009]) in the expression of the sine-generated curve. The styles of meandering reported in *Lagasse et al.* [2004] classification (Figure 2) suggest that channel width might also be described through a regularly oscillating function, with half the curvature wavelength, namely for the "wider-at-bends" class.

At a first approximation, the planform of a meander with spatially variable width and intrinsic wavelength L^* can therefore be represented by two oscillating functions of the arclength describing the spatial distribution of channel width and curvature, with the curvature wavelength being twice that of the width oscillations $L^* = 2L_w^*$. For sine-generated meanders four main parameters are therefore needed: meander wavelength, amplitude of curvature and width oscillations and the phase lag between the two functions. To substantiate this assumption and to translate it into quantitative terms, it has been tested against real meandering rivers data.

Besides the large *Lagasse et al.* [2004] dataset, an active meandering reach of the Rio Beni in the Bolivian Amazon has been specifically chosen for this purpose. The Beni is a large southern tropical river draining the Andean and sub-Andean ranges and flowing into the Madeira River [*Gautier et al.*, 2007]. The reach is freely evolving, without significant anthropic effects and with relatively homogeneous hydraulic and sediment conditions along tenths of subsequent meander bends. It is of particular interest for the present study because it shows wider-at-bends sections with frequent mid-channel bars and islands (see also Figure 1b). Figure 4 shows the longitudinal distributions of the bankfull width, computed assuming that areas of bare sediment at low flows are submerged at bankfull. In most of the bends the width exhibits at least one significant peak between two subsequent meander inflections. This agrees with analogous observations reported by *Luchi et al.* [2011] based on data from a different reach of the same Rio Beni and is also consistent with the outcomes of *Luchi et al.* [2010a] on a much different meandering river system (River Bollin, UK).

The four parameters used to describe the river planform are expressed in dimensionless form for consistency with the modelling approach described in the next section. They are defined as follows:

$$\nu = \frac{W_0^*}{2R^*}; \quad \delta = \frac{(W_{max}^* - W_0^*)}{2(W_0^*)}; \quad \lambda = \frac{\pi W_0^*}{L^*}; \quad \lambda_w = 2\lambda. \tag{1}$$

In (1) a star (*) denotes dimensional quantities; λ represents the dimensionless meander wavenumber, taken as half the spatial frequency λ_w of width oscillations. Moreover L^* is meander intrinsic wavelength, W_0^*, W_{max}^* are the reach-averaged and maximum values of channel width, and ν, δ denote the dimensionless amplitudes of curvature and width oscillations, respectively. R^* is a typical measure of the channel axis radius of curvature; for a sine-generated meandering planform it has been often assumed equal to twice the minimum value at the bend apex. The spatial curvature $\mathcal{C}^*(s) = 1/R^*(s)$ and width distributions are made dimensionless with $2/W_0^*$ and W_0^* respectively. for a sine-generated meandering channel they can therefore be expressed through the dimensionless oscillating functions $\mathcal{C}(s)$ and $W(s)$ defined as follows:

$$\frac{W_0^*\mathcal{C}^*(s)}{2} = \mathcal{C}(s) = \nu\left[\exp\left(i\lambda s\right) + c.c\right] \tag{2}$$

$$\frac{W(s)}{W_0^*} = W(s) = 2 + 2\delta\left[\exp\left[i\left(\lambda_w s + 2\omega\right)\right] + c.c.\right]; \tag{3}$$

with *c.c* denoting the conjugate of a complex number and ω the phase lag between the widest and the most curved section.

The ratio $R^*/W_0^* = 1/(2\nu)$ has been subject of many quantitative analysis because of its fundamental relevance for meander dynamics. *Hickin and Nanson* [1984], *Hudson and Kesel* [2000], *Crosato* [2009], among others, pointed out the R^*/W_0^* range corresponding to the maximum meander migration rate, while *Hooke and Harvey* [1983] developed a classification model for meander migration and loop shape based on the values of R^*/W_0^* and of the meander path length ($L^* = \pi W_0^*/\lambda$).

Much less attention has been paid to quantify δ in meandering rivers. *Luchi et al.* [2011] have estimated the values of δ by analyzing the standard deviation of the spatial width distribution extracted for 31 bends of the Rio Beni. In most of the examined bends, peak width values have been observed not to exceed 1.4 times the reach-averaged channel width, corresponding to δ values (1) below 0.2.

We have tested these findings using data for wider-at-bends meanders (class C in Figure 2) reported in *Lagasse et al.* [2004] that contains information of maximum and reach-averaged channel width. Equation (1) has been applied to all bends, which have been grouped into classes of similar meander wavenumber λ. The outcomes, represented in Figure 5 in the form of box plots, are consistent with the findings of *Luchi et al.* [2011] on the Rio Beni. Average δ values are typically slightly lower than 0.1, corresponding to the widest section less than 20% wider than the wavelength-averaged value. The largest scatter is displayed by individual bends whose length is between 9 to 13 times the average channel width ($0.25 < \lambda < 0.35$). The 84th percentile of all δ values never exceeds 0.13, with outliers $\delta \simeq 0.2$ for very few bends ($< 5\%$).

Figure 5b shows the same distributions for the dimensionless curvature amplitude ν obtained from the same bends. Median values of ν show a regular increase with λ: this might be associated with the tendency of channel curvature to vary more rapidly in space when bends are shorter.

Luchi et al. [2011] have quantified also the distance between the widest section and the bend apex. In the examined reach of the Rio Beni this relative distance can be relatively high, normally keeping less than half the bend length (i.e. one quarter the meander wavelength L^*) for all bends. Only for a few bends is the maximum of channel width located closer to the meander inflections. Although the available data refer to only one river reach, no clear trend has been detected for the dimensionless phase lag ω between the width and curvature distributions.

Consistently with the few published data on the spatial series of width and curvature in real meandering rivers, the present analysis indicates that the dimensionless amplitudes of both distributions are "small". This suggests the suitability of a perturbation approach to seek for simplified analytical solution of the mathematical problem, which is formulated in the next section.

4. Hierarchy of Morphodynamic Models for Meandering Channels with Spatial Width Variations

The model formulated in the present section refers to the flow-bed topography deformation in meandering channels with spatially varying width. It essentially focusses on instream processes occurring in the central flow region. The dynamics of bank processes is accounted for through the simplified and widely adopted relation between bank migration and the near-bank instream flow field [*Partheniades and Paaswell*, 1970]. It stipulates that the bank erosion (accretion) rate is linearly related to the excess (defect) near-bank shear stress relative to a reach-averaged value. This assumption leads to the well known lateral channel migration law employed in most meander models (e.g. *Ikeda et al.* [1981]), which reads, in dimensionless form:

$$\zeta(s) = E\left[u_{lb}(s) - u_{rb}(s)\right], \tag{4}$$

where $\zeta(s)$ denotes the net rate of channel shift, assumed positive in the direction locally normal to the left bank and aiming outwards, s is the streamwise coordinate, u_{lb} and u_{rb} represent near-bank (left and right respectively) excess longitudinal velocity, and E is an empirical erosion coefficient which reflects bank properties [*Hasegawa*, 1989] computational choices in the numerical scheme of meander planform evolution [*Crosato*, 2007] and floodplain heterogeneities [*Güneralp and Rhoads*, 2011].

4.1. Mathematical Formulation

The modelling tool chosen for the present work is based on a depth-averaged morphodynamic model forced by the spatial variations of channel width $W^*(s)$ and curvature $\mathcal{C}^*(s) = r_0^{*-1}$. This follows a rather established approach in meander morphodynamics and relaxes the assumption of a constant channel width typical of established meander evolution models. The valley slope is assumed constant and the cohesionless bed is composed of uniform sediment size. The formulation refers to an intrinsic curvilinear coordinate system (s^*, n^*) that is right handed and orthogonal with the s^* axis locally downstream directed (Figure 6). The analysis is based on typical assumptions for large-scale river morphodynamic modelling. Namely it is referred to the central region of the cross section, it ignores the side boundary layers, it assumes a shallow water approximation and a slowly varying flow field in space. Moreover steady conditions for flow and bed topography are assumed considering a typical hierarchy of scales whereby planform geometry varies on a much longer time scale with respect to bed deformation, and to flow unsteadiness.

The depth averaged, steady formulation of the morphodynamic problem accounting for both curvature and width variations is formulated in dimensionless form with all the variables normalized through reach-averaged quantities in order to achieve more generality and to facilitate comparison of the relative magnitude of different physical effects. The normalizing scales refer to a uniform flow in a straight channel that carries the same discharge, with the same mean sediment size d_s^* and slope S. The uniform flow depth is denoted with D_0^*.

The normalization procedure allows to point out the key dimensionless parameters: the aspect ratio β, the relative roughness d_s and the Shields stress τ_*. They are computed as follows using the reference uniform flow values, with Δ denoting the relative sediment submerged density:

$$\beta = \frac{W_0^*}{2D_0^*}, \quad d_s = \frac{d_s^*}{D_0^*}, \quad \tau_* = \frac{S}{\Delta d_s}. \tag{5}$$

The morphodynamic model can be expressed in the following form:

$$UU_{,s} + VU_{,n} + H_{,s} + \frac{\beta\,\tau_s}{D} + f_\alpha = f; \tag{6}$$

$$UV_{,s} + VV_{,n} + H_{,n} + \frac{\beta\,\tau_n}{D} + g_\alpha = g; \tag{7}$$

$$(DU)_{,s} + (DV)_{,n} = m; \tag{8}$$

$$Q_{s,s} + Q_{n,n} = p. \tag{9}$$

In equations (6, ..., 9), U and V denote depth averaged flow velocity in the longitudinal and transverse direction respectively, H is the free surface elevation and D the local depth. (τ_s, τ_n) and (Q_s, Q_n) are the bottom shear stress and sediment rate vectors. Moreover f_α and g_α are homogeneous terms accounting for the effect of streamline curvature on the parameterization of secondary flows (see *Luchi et al.* [2011]), which vanish when secondary flows are parameterized using the channel axis curvature.

The forcing terms $\mathcal{F} = (f, g, m, p)$ in the right hand side of the differential system (6, ..., 9) can be written according to the same general structure:

$$\mathcal{F} = \nu\,\mathcal{F}_{10} + \delta\,\mathcal{F}_{01} + \nu^2\mathcal{F}_{20} + \nu\,\delta\,\mathcal{F}_{11}, \tag{10}$$

which easily allows to distinguish between the forcing effects of width and curvature variations on the morphodynamic response of the system. The forcing effect of curvature is due to both first ($\mathcal{O}(\nu)$) and second ($\mathcal{O}(\nu^2)$) order terms and would appear also in meandering channels with constant width. Channel width variations force the system in the form of a first-order contribution $\mathcal{O}(\delta)$ that coincides with that corresponding to a straight channel with variable width. Moreover the $\mathcal{O}(\nu\delta)$ term represents the mixed effect due to width and curvature variations. Higher order terms in ν and δ and in their combinations are supposed to play a minor role. The complete expression of these forcing terms are reported in *Luchi et al.* [2011].

Finally, lateral boundary conditions to be associated with equations (6, ..., 9) impose that the lateral walls must be impermeable both to fluid and sediments.

4.2. Two-parameter Perturbation Solution Scheme

The data analysis of Section 3 has indicated that for wider-at bends meandering streams the dimensionless amplitude δ of width oscillations is a "small" number in analogy with the amplitude ν of curvature variations (Figure 5). Together with the structure of the forcing term (10), this suggests to employ a perturbation approach to study the dynamic role of width variations in meanders, analogous to that used in equiwidth meanders where the sole forcing effect is a spatially variable channel curvature. This slightly complicates the mathematical solution with respect to the equiwidth case because a two-parameters (ν

and δ) perturbation approach is required. In order to focus on the key physical processes and on the basis of the analysis described in the previous section, the solution is referred to an idealized meandering planform consisting of an indefinite sequence of sine-generated meander bends (*Langbein and Leopold* [1964]) and width oscillating with half the curvature wavelength (2,3).

The model ($6 \ldots 9$) with boundary conditions is solved expanding the unknowns vector $\mathbf{V}$ in powers of the two perturbation parameters ν and δ as follows:

$$\begin{aligned} \mathbf{V} &= \mathbf{V_0} + \nu \mathbf{V}_{10} + \nu^2 \mathbf{V}_{20} + \delta \mathbf{V}_{01} + \nu\delta \mathbf{V}_{11}; \\ \mathbf{V} &= (U, V, H, D); \quad \mathbf{V_0} = (1, 0, H_0(s), 1); \\ \mathbf{V}_{kj} &= (U_{kj}, \ldots, D_{kj}); (k = 0, 1, 2;\ j = 0, 1), \end{aligned} \tag{11}$$

a structure which is suggested by the right-hand side of (6, ..., 9). On substituting (10) into (6, ..., 9) and into the boundary conditions, linear differential systems are obtained at each order of approximation, which admit for exact analytical solutions, each one corresponding to a different physical mechanism:

- $\mathcal{O}(\nu)$: the flow and bed topography component linearly forced by curvature in meanders with constant width;
- $\mathcal{O}(\nu^2)$: the second-order non linear component of flow and bed topography forced by curvature in meanders with constant width;
- $\mathcal{O}(\delta)$: the flow and bed topography component linearly forced by width variations in straight channels with variable width;
- $\mathcal{O}(\nu\delta)$: the first nonlinear interaction which expresses the mixed response for flow and bed topography in meanders with variable width.

Solutions at each of the above orders of approximation can be obtained separately because (ν, δ) can be assumed of the same order of magnitude and the spatial structure of the solutions with the same orders of magnitude ($\mathcal{O}(\nu), \mathcal{O}(\delta)$ and $\mathcal{O}(\nu^2), \mathcal{O}(\nu\delta)$) is different in both the (s, n) directions.

The next two sections have separate focuses on linear and nonlinear responses. The outcomes of linear solutions are quite established in meander modelling; combining these with the analysis of the nonlinear responses provides key ingredients to answer the research questions posed in the Introduction.

5. Linear Models

5.1. Equiwidth Meander: $\mathcal{O}(\nu)$

The bed deformation and lateral migration processes occurring in equiwidth meanders have been extensively modelled through linear models [*Camporeale et al.*, 2007]) commonly used to compute local migration rates in numerical models of long term planimetric evolution (*Howard* [1992], *Seminara et al.* [2001], *Camporeale et al.* [2005]). Channel curvature is typically associated with laterally antisymmetric bed patterns: sequences of scour - deposition zones alternately spaced across the lateral and longitudinal direction. This causes an excess longitudinal velocity at one bank with respect to the reference uniform flow, and a symmetrical defect at the opposite bank. In terms of bedform, the $\mathcal{O}(\nu)$ solution reproduces the classical point bar morphology (see the corresponding sketch in the left column of Figure 12). It forces a laterally symmetrical pattern of the transverse velocity V_{10} and a lateral antisymmetric structure of the longitudinal velocity U_{10} and of the bed profile $\eta_{10} = F_0^2 H_{10} - D_{10}$ with the same longitudinal periodicity of the curvature (eqn.

2). The bed pattern is given by:

$$\begin{aligned}\eta_{10} &= \left[\alpha n + \sum_{j=1}^{2} \gamma_j \sinh\left(\lambda_{j\nu} n\right)\right] e_1(s) + c.c. = \\ &= \eta_{1\nu}(n) e_1(s) + \overline{\eta}_{1\nu}(n) \overline{e}_1(s),\end{aligned} \quad (12)$$

where $e_k = \exp\left(k\, i\lambda s\right)$ (k integer), $\alpha, \gamma_1, \gamma_2, \lambda_{1\nu}, \lambda_{2\nu}$ are complex numbers and an overbar denote complex conjugates. Mathematically the solution procedure is formally identical to that of *Blondeaux and Seminara* [1985], with some differences in the governing equations.

Meander evolution has been studied as a bend instability process considering that perturbations of channel axis alignment with respect to a straight configuration may grow in time thus developing a meandering pattern. *Unstable* bends are defined as those that tend to further grow eventually leading to meander amplification. The stability of the small-amplitude sinusoidal perturbations of the channel axis depend on the phase lag between the perturbation of the longitudinal velocity $U_{10}(s, n = 1)$ (see eqn. 4) and the curvature distribution. The highest migration rate is expected at the cross-section where the maximum difference between right and left bank excess longitudinal velocity occurs.

5.2. Straight Channels with Spatial Width Oscillations: $\mathcal{O}(\delta)$

Differently from curvature, spatial width variations force a laterally symmetrical flow-bed topography pattern. In this sense they represent a complementary planform effect with respect to curvature. As a result a central bar pattern is obtained, which tends more often, although not invariably, to appear in the widest sections, thus eventually promoting the growth of the width oscillations through a planform stability mechanism analogous to that of bend stability. *Repetto et al.* [2002] proposed an analytical model for the occurrence of mid-channel bars in straight channels with sinusoidal width variations and discussed the role of central bars in triggering bifurcation of the stream and thus potentially initiating a braided pattern. The solution displays an antisymmetrical lateral structure of the transversal velocity V_{01} and a laterally symmetrical pattern of the longitudinal velocity U_{01} and of the bed profile $\eta_{01} = F_0^2 H_{01} - D_{01}$:

$$\begin{aligned}\eta_{01} &= [\alpha_1 \cosh(\lambda_{1\delta} n) + \alpha_2 \cosh(\lambda_{2\delta} n)]\, e_2 + c.c. = \\ &= \eta_{1\delta}(n) e_2(s) + \overline{\eta}_{1\delta}(n) \overline{e}_2(s). \end{aligned} \quad (13)$$

The longitudinal periodicity is that of the width variations (eqn. 3); $\alpha_1, \alpha_2, \lambda_{1\delta}, \lambda_{2\delta}$ are complex numbers. The bedform pattern at the $\mathcal{O}(\delta)$ is illustrated by the corresponding planform in the left column of Figure 12.

The concept of planform stability applied to this case implies that unstable planforms at the $\mathcal{O}(\delta)$ will tend to widen the widest section and thus can be interpreted as initiators of a multi-thread pattern. The analysis of *Repetto et al.* [2002] indicates that this planform instability theoretically occurs for long wavelengths ($\lambda_w \leq 0.15$, see also their Figure 22).

Luchi et al. [2010b] proposed that the linear mechanism theoretically studied by *Repetto et al.* [2002] can be a possible cause of mid-channel bar growth also when the channel axis has a meandering planform. This can occur when spatial width variations are already present, as when they originate because the advance rate of one bank cannot keep the pace of the opposite eroding bank (Figure 7). This can be referred to as a *width-forced* mechanism for mid-channel bar generation. It requires that different processes operate at opposite banks in the same cross-section. Such process has been documented by *Hooke* [1986] and *Hooke and Yorke* [2011], who indicated that widening preceded central bed deposition at most of the field sites.

Recently, the model of *Repetto et al.* [2002] has been extended to the case of arbitrarily varying spatial width variations by *Frascati and Lanzoni* [2011]. This analysis is relevant for meandering rivers because is allows to compute their complete linear response to arbitrarily varying curvature and width: it results from truncating the expansion (10) at the first two terms and relaxing the periodicity assumption of (2) and (3).

6. Nonlinear Models

6.1. Mid-channel Bars in Equiwidth Meanders: $\mathcal{O}(\nu^2)$

The presence of width variations and mid-channel bars in meanders is a typical chicken-egg question: which of them does originate first? The linear, width forced mechanism proposed by *Repetto et al.* [2002] and *Luchi et al.* [2010b] requires width variations to exist prior to mid channel bars, like when opposite banks respectively experience accretion and erosion.

A complementary process is the generation of width oscillation because of flow divergence around existing mid-channel bars in originally equiwidth channels. This implies that both banks in the same cross section are both subject to erosion, as in the section of the River Bollin reported in Figure 9a. This has nearly vertical sidewalls and a transversally symmetrical topographic high corresponding to a mid-channel bar pattern. Mathematically channel curvature can promote laterally symmetrical patterns at the $\mathcal{O}(\nu^2)$ solution, which applies to a meander with constant width. Such possibility has been experimentally substantiated by *Colombini et al.* [1992] on a sinusoidal, equiwidth meandering flume. The analysis of the steady bed topography (see Figure 23.9 in *Colombini et al.* [1992]) pointed out that the amplitude of the mid-channel bar component of the bed topography can be up to half that of the point bar. Mid-channel bars are therefore not exclusively associated with pre-existing spatial width variations, but can develop in equiwidth meanders because of nonlinear effects.

The longitudinal and lateral structure of the second order solution $\mathbf{V_{20}}$ is determined by flow nonlinearities of the governing differential system (6 ... 9). At the $\mathcal{O}(\nu^2)$, as well as at each order of approximation, the solving differential system is linear. Therefore the structure of the solution closely matches that of the forcing terms. For instance, the term $UV_{,n}$ in the longitudinal momentum equation produces a forcing term due to the product of two first-order contributions:

$$\begin{aligned} V_{10}U_{10,n} &\Rightarrow \left(V_{1\nu}e_1 + \overline{V}_{1\nu}\overline{e}_1\right)\left(U_{1\nu,n}e_1 + \overline{U}_{1\nu,n}\overline{e}_1\right) \\ &= V_{1\nu}U_{1\nu,n}e_2 + V_{1\nu}\overline{U}_{1\nu,n}e_0 + c.c.; \end{aligned} \quad (14)$$

where we have employed analogous notations of equation (12) to express the lateral structures of V_{10} and U_{10}. In general, this implies that forcing terms for the longitudinal momentum, flow and sediment continuity equations are laterally symmetric. This is reflected in the solution for $\mathbf{V}_{20}$: in the s-direction the solution is the sum of one longitudinally oscillating component ($\propto e_2$) with twice the meander wavenumber (2λ) and one longitudinally invariant response ($\propto e_0$). The bed profile at the $\mathcal{O}(\nu^2)$ can be written as:

$$\eta_{20} = \left(\eta_{20}^{(2)}(n)e_2 + c.c.\right) + \eta_{20}^{(0)}(n)e_0; \quad (15)$$

being $\eta_{20}^{(2)}$ and $\eta_{20}^{(0)}$ even functions of n. The corresponding pattern is illustrated in the left column of Figure 12.

In order to relate the $\mathcal{O}(\nu^2)$ solution to processes occurring in a real meandering river, we have applied it to a reach of the River Bollin (NW England; Figure 8a), a gravel-bed meandering river whose high lateral mobility makes it particularly suitable to study meander processes [*Hooke*, 2004]. The development of a mid-channel bar has been observed between years 2008 and 2009 in several inflection regions like those appearing in Figure 8a. The subsequent bar growth can be assessed by visually comparing Figures 8b and D, which have been taken before and after several channel-forming events. At formative conditions the Bollin has a nearly constant active channel width in space, i.e. the width of the cross-section that is actually capable to transport sediments [*Luchi et al.*, 2012]. Therefore the observed mid-channel bar cannot be attributed to a width-forced linear mechanism like that modelled by *Repetto et al.* [2002], but rather to a mechanism operating in equiwith meanders, like that corresponding to the $\mathcal{O}(\nu^2)$ solution.

Based on input parameters representative of formative conditions, the analytical solution easily allows to compute the position and the amplitude of the mid-channel bar and related flow field along the meander according to such *curvature-driven* mechanism. In Figure 8C the quantity φ_{η_2} is the phase lag between the most curved cross-section and the peak of $\eta_{20}^{(2)}(n=0)$, which corresponds to the mid-channel bar component of bed elevation evaluated at the centerline. The continuous line indicates how the position of the central bar top varies along half the meander wavelength (sketched in the left panel), depending on the value of the dimensionless meander wavenumber λ. The wavenumber of bends in the analyzed reach of the Bollin varies between 0.17 and 0.29, a range where the model indicates a tendency to develop a central response close to meander inflection. This is in good agreement with field analysis on the bed topography of *Luchi et al.* [2010a] that pointed out the presence of an incipient mid channel bar at an inflection area between two bends of similar wavenumber nearly equal to 0.19. The associated sections present an evident laterally symmetrical, central bed topography pattern (Figure 9a) and the plot in Figure 8D provides evidence of its permanence after some channel forming events.

An option to to distinguish between the curvature-driven and width-forced mechanisms for mid-channel bars with the aid of models can be based on the predicted location of the mid-channel bar by the two mechanisms, as also illustrated by *Luchi et al.* [2010b] and *Zolezzi et al.* [2011] referring to the meandering gravel-bed rivers Dane and Dean in NW England. This has received some support also by the recent field study of *Hooke and Yorke* [2011], which indicates that in the Dane mid-channel bars are width induced as theoretically predicted.

Examining the location of the longitudinal velocity peak at the banks as predicted by the $\mathcal{O}(\nu^2)$ solution shows how these curvature forced mid-channel bars can be a cause for width variations. The dashed line in Figure 8 indicates the phase lag φ_{U_2} of the symmetrical bank-excess longitudinal velocity associated with the presence of a central topographical pattern. The fact that $\varphi_{\eta 2}$ is always larger than φ_{U_2} indicates that the excess near-bank longitudinal velocity locates downstream of the mid-channel bar tops. This condition is almost invariably verified for values of $(\lambda, \beta, \tau_*, d_s)$ typical of gravel bed rivers. As far as the near-bank excess longitudinal velocity can be assumed to be positively correlated with bank erosion - as assumed in most meander migration models (*Hasegawa* [1989], *Ikeda et al.* [1981]) - it can be expected that the presence of a mid-channel bar would be associated with a cross-sectionally symmetrical bank erosion just a few channel widths downstream the mid-channel bar top, thus determining a tendency to local cross-sectional widening.

Analogously, a central scour hole would occur half a meander wavelength downstream the central bar deposit, triggering flow convergence which, according to model predictions, would cause a peak of the main flow thread in the central portion of the channel a few widths downstream the scour region itself. This section is expected to be subject to the maximum narrowing tendency. The overall process tends to cause planform deformation from an equiwidth meander (continuous banklines in Figure 9b) to a meander with variable width (dashed banklines) and can be referred as a laterally symmetrical mechanism for the generation of spatial width oscillations in meanders.

Finally, the $\mathcal{O}(\nu^2)$ solution consistently predicts an increasing relative amplitude of the mid-channel bar component of bed topography with respect to that of the point bar ($\mathcal{O}(\nu)$) for decreasing meander wavelength - i.e. increasing meander wavenumber λ (see also Figure 11a).

6.2. Effect of Width Variations on Meander Bend Growth: $\mathcal{O}(\nu\delta)$

The $\mathcal{O}(\nu^2)$ solution suggests that curvature variations can promote channel width variations through a laterally symmetrical mechanism. The mixed $\mathcal{O}(\nu\delta)$ solution allows to investigate whether a reciprocal effect can also take place, i.e. whether the presence of width variations may affect channel curvature therefore affecting meander growth.

The $\mathcal{O}(\nu\delta)$ solution quantifies the correction to the linear $\mathcal{O}(\nu)$ bend stability due to the presence of width variations. This mutual nonlinear interaction gives rise to forcing terms with the same symmetry properties of the $\mathcal{O}(\nu)$ solution; laterally antisymmetric for the longitudinal momentum, water and sediments continuity equations, symmetric for the lateral momentum equation. For instance, the example term $UV_{,n}$ produces forcing contributions which take the form:

$$V_{01}U_{10,n} \Rightarrow \left(V_{1\delta}e_2 + \overline{V}_{1\delta}\overline{e}_2\right)\left(U_{1\nu,n}e_1 + \overline{U}_{1\nu,n}\overline{e}_1\right)$$
$$= V_{1\delta}\overline{U}_{1\nu,n}e_1 + V_{1\delta}U_{1\nu,n}e_3 + c.c. \qquad (16)$$

The above structure is reflected in the solution for $\mathbf{V_{11}}$. The $\mathcal{O}(\nu\delta)$ is the lowest order at which the nonlinear interaction between curvature and width forced solutions reproduces the longitudinal structure of the fundamental linear solution ($e_1 + cc.$). This is related to the assumption $\lambda_w = 2\lambda$ that represents a key specificity of the adopted perturbation scheme. The bed topography pattern at the $\mathcal{O}(\nu\delta)$ has also a similar antisymmetric transversal pattern to that at the $\mathcal{O}(\nu)$ (Figure 12 and eqn. 12), although with different eigenfunctions, phase lags and amplitude.

In a meander with width variations, the perturbation scheme (10) indicates that $U(s, n = 1)$ is the sum of five main effects. The migration law (4) however suggests that even functions of the lateral coordinate n do not contribute to meander migration. Therefore only the $\mathcal{O}(\nu)$ and the $\mathcal{O}(\nu\delta)$ solutions control meander migration and stability. Accounting for the laterally antisymmetrical character of U_{10} and of U_{11}, it follows:

$$\zeta(s) \sim \nu\left[U_{10}(s, n = 1) + \delta U_{11}(s, n = 1)\right]. \qquad (17)$$

The $\mathcal{O}(\nu\delta)$ is therefore the first interaction at which an effect on bend stability can be reproduced: due to the assumption $\lambda_w = 2\lambda$, the $\mathcal{O}(\nu\delta)$ velocity perturbation has the same longitudinal structure of the fundamental $\mathcal{O}(\nu)$ perturbation.

The results can be summarized in a marginal stability plot in the $(\lambda - \beta)$ plane for given values of (τ_*, d_s) (Figure 10). The marginal curves in Figure 10 separate unstable (left) from stable (right) meander wavenumbers. The curve with $\delta = 0$ corresponds to the result of the classical equiwidth linear bend theory - $\mathcal{O}(\nu)$ - while $\delta = 0.5$ is the upper limit for geometrically meaningful planform configurations. The curves corresponding to intermediate δ values indicate that, for typical aspect ratios of meandering rivers, width variations tend to shift the instability region towards values of $\lambda \sim 0.2 - 0.3$, their effect being stronger for intermediate values of β, between 10 and 25 for typical formative conditions of gravel-bed rivers. Also the wavenumber corresponding to the maximum bend amplification rate may increase. This implies that width variations are expected to destabilize shorter meander bends with respect to those predicted by classical linear bend theories in equiwidth meanders.

This may partially correct the systematical wavelength overestimation achieved by equiwidth linear bend theories of incipient meanders shown in Figure 10, which compares predicted and measured intrinsic wavenumbers of some low sinuous rivers extracted from the dataset of *Hey and Thorne* [1986]. Accounting for the presence of width variations can reduce this systematic gap.

A second important feature of the mixed response is its tendency to produce two markedly separated most unstable longitudinal modes λ associated with two distinct peaks in the meander bend growth rate, represented by the function $\mathrm{Re}(U_{11})$ (plotted in Figure 11b as function of meander wavelength). This behavior represents a marked difference with respect to equiwidth meanders, for which bend instability is characterized by the presence of a single unstable range of longitudinal modes. Meanders with intense enough spatial width variations, and at sufficiently large bankfull aspect ratio, might therefore display a long term tendency towards almost two different equally unstable planforms characterized by well distinct meander wavelengths. *Luchi et al.* [2011] have been put this in qualitative relationship with the reach-scale occurrence of chute cutoffs that has been preferentially observed in meanders with spatial variations of channel width (*Lagasse et al.* [2004] based on *Brice* [1975]).

7. Discussion

The implications of the outcomes of the perturbation modelling approach illustrated in the previous sections are here discussed in the light of the three research questions posed in the Introduction.

7.1. Role of Flow Nonlinearities in Meandering Rivers with Spatial Width Variations

The first research question focuses on the main physical processes that occur in rivers at the meandering-braiding transition. Although the complete mathematical model accounts for both linear and nonlinear processes, nonlinearity of flow and bed topography turns out to be the main distinctive feature of meanders with spatial width variations, because of its fundamental control on planform stability. Mid channel bars can spontaneously develop in equiwidth meanders through nonlinear, curvature-forced effects and might trigger spatial width oscillations. Width oscillations nonlinearly affect bend stability by shortening the unstable meander bends and by determining multiple instability peaks associated with two separate most unstable wavelength ranges.

Figure 11 combined with the field observations reported in Figure 3 can be used to show that nonlinear effects are the fundamental ingredient to explain the observed differences between equiwidth and wider-at-bends meanders.

Figure 11 couples outcomes from the nonlinear $\mathcal{O}(\nu^2)$ (a) and $\mathcal{O}(\nu\delta)$ (b) solutions. Figure 11a is based on Figure 10 of *Luchi et al.* [2010b] and refers to the experimental observations of *Colombini et al.* [1992] on regular sequences of small amplitude meanders with constant width. It compares experimental results and model predictions for the amplitude ratio between the mid-channel bar ($\mathcal{O}(\nu^2)$) and point bar ($\mathcal{O}(\nu)$) components of bed topography. As verified experimentally, shorter meanders tend to have an increasing dominance of the central bar component in the bed composition; they can therefore be expected to exhibit a stronger tendency to develop spatial width oscillations according to the autogenic, symmetrical mechanism illustrated in Figure 9b. Figure 11b (based on Figure 8b of *Luchi et al.* [2010b]) shows the difference between predicted growth rate of equiwidth ($\mathcal{O}(\nu)$) and wider at bends ($\mathcal{O}(\nu) + \mathcal{O}(\nu\delta)$) meandering rivers. Spatial width variations cause a shift of the bend instability region towards shorter meanders, coherently with the results shown in Figure 3. This can be seen from the dashed line - $\mathcal{O}(\nu\delta)$ - intersecting the horizontal axis at smaller values of meander wavelength compared to the continuous line - $\mathcal{O}(\nu)$. Moreover the peak in the dashed line at $L^*/W^* \sim 18 \div 20$ exemplifies the tendency to develop two separate most unstable wavelength ranges, which is absent in linear meander models. This effect on meander wavelength selection may in turn condition the nonlinear growth of meander loops with important implications also for long-term simulations [*Frascati and Lanzoni*, 2009], meander loop shape [*Hooke and Harvey*, 1983] and migration rates [*Crosato*, 2008].

Both the above-mentioned effects are intrinsically nonlinear and indicate that the presence of mid-channel bars and of spatial width variations tends to be associated with shorter meander bends compared to their equiwidth counterparts. This is in good qualitative agreement with the field observations reported in Figure 3b. The presence of multiple unstable longitudinal modes and of a richer content of transverse bed topography modes like mid-channel bars also suggests that meanders close to the transition with braided rivers shall display a higher rate of morphological activity, which also qualitatively agrees with the observations of *Lagasse et al.* [2004] reported in Figure 3a.

Finally, the effect of nonlinearity in meandering morphologies close to the transition with braiding shall be accounted for into physics-based channel pattern predictors based on linear theories for free migrating [*Parker*, 1976; *Fredsœ*, 1978] and forced steady [*Crosato and Mosselman*, 2009] bars. These predictors compute the most probable lateral number m of bars for reach-averaged, representative values of discharge, sediment size, longitudinal slope and bankfull width, with the predicted value of m increasing with channel aspect ratio β. When alternate bars ($m = 1$) are the most probable, a single-thread, meandering pattern is predicted; transitional morphologies correspond to $1.5 < m < 2.5$ and braiding to $m > 3$. Nonlinearities in transitional meanders may imply the formation of mid-channel bars ($\mathcal{O}(\nu^2)$) large enough to produce a mid-channel bar configuration ($m = 2$) that corresponds to a transitional morphology for β values smaller than those predicted on the basis of linear bar theories.

7.2. Cause-Effect Relationships between Mid-Channel Bars and Width Variations in Meandering Rivers

Coupling linear $\mathcal{O}(\delta)$ with nonlinear $\mathcal{O}(\nu^2)$ models and examining cross sectional profiles from real meandering rivers (Figures 7 and 9a) allows to propose a possible key to disclose the chicken-egg question about cause-effect relations between mid-channel bars and width variations in meandering rivers. A laterally symmetric and a laterally asymmetric mechanisms are proposed as possible causes for spatial width variations in curved channels. Their main properties are summarized in Table 2. In the symmetrical mechanism, mid-channel bars due to morphodynamic nonlinearities ($\mathcal{O}(\nu^2)$) force width variations. On the contrary, width variations associated to the asymmetrical mechanism force mid channel bars as a linear bed response ($\mathcal{O}(\delta)$).

The local unbalance between erosion and accretion processes at opposite banks can be referred to as a laterally asymmetrical mechanism (Figure 7). The bank profiles in typical bend sections (Figure 9a) are asymmetrical, with the eroding bank showing a nearly vertical profile and the accreting bank gently sloping. Locally channel width tends to change when erosion and accretion do not keep the same pace. This is largely determined by bank-related processes, which are not the subject of a detail analysis in the present work.

The symmetrical mechanism is suggested by the central bed topography pattern in the cross-sectional profile shown in Figure 9b and by the lateral sidewalls being both close to vertical. This suggests that opposite banks at the same cross section must be subject to erosion. As sketched in Figure 9b, the steering topographical effect associated with curvature-driven mid-channel bars can force the flow to diverge against both banks, thus inducing laterally symmetrical bank erosion, which eventually results in cross-sectional widening.

7.3. Linking Planform Stability Models with Classification of Meandering River Patterns

The third research question of the present work relates to the possibility of understanding differences between meandering styles through physically-based mathematical models. To make a first step in this direction, the present modelling framework can be put in qualitative relation to the form-based classification of meandering patterns originally proposed by *Brice* [1975] and lately refined by *Lagasse et al.* [2004]. This is achieved in a process-oriented perspective in Figure 12, which links (arrows) the meandering styles proposed by *Lagasse et al.* [2004] (right column) with the planform stability properties as predicted at the different orders of approximation $\mathcal{O}(\nu), \mathcal{O}(\delta), \mathcal{O}(\nu^2), \mathcal{O}(\nu\delta)$ within the present modelling framework. Moreover the planform and the flow-bedform pattern corresponding to each order is reported in the left column.

Equiwidth meandering patterns (like type-B_1) are predicted by the fundamental process of bend instability [*Ikeda et al.*, 1981], which generates Kinoshita-type meanders through geometric nonlinearities [*Seminara et al.*, 2001]. Bend instability selects long enough meander wavelengths while shorter perturbations are stable thus promoting channel straightening. Multi-lobed patterns like G_1 are associated with the progressive elongation of meander bends which promotes the instability of higher planform harmonics (*Camporeale et al.* [2007], *Zolezzi et al.* [2009]).

Meandering patterns that approach the transition with braiding are characterized by the presence of spatial width variations. Following *Brice* [1975]'s classification, two major classes can be distinguished, depending on chutes being rare (classes B_2, C, E and G_2) or common (class D). The linear - $\mathcal{O}(\delta)$ - and nonlinear - $\mathcal{O}(\nu^2), \mathcal{O}(\nu\delta)$ - instream processes described by the proposed modelling framework can play a relevant role in their morphodynamics.

The oscillations in width may be initiated due to a laterally symmetrical and a laterally antisymmetrical mechanism (Table 2). The analysis at the $\mathcal{O}(\nu^2)$ has shown that every meandering channel has an intrinsic tendency to develop mid-channel bars that eventually determine symmetrical flow divergence against both banks. This is likely to trigger symmetrical bank erosion slightly downstream of the mid-channel bar location, thus producing longitudinal width oscillations at a double frequency with respect to curvature variations. The intensity of such process is predicted to crucially depend on meander wavelength, being higher for shorter meander bends.

On the contrary, when erosion and accretion occur at the opposite banks of the same cross-section, widening (narrowing) can be produced by an asymmetrical mechanism as far as the two processes do not keep the same pace [*Nanson and Hickin*, 1983]. As widening and narrowing cannot indefinitely grow in time, also cyclic width variations in time can be expected. Although already argued by *Parker et al.* [2011], quantitative field evidence and modelling of such temporal oscillations have not been provided so far.

Once initiated, longitudinal width oscillations can increase their amplitude in time according to the linear planform instability mechanism detected by *Repetto et al.* [2002], who showed that only long wavelengths ($\lambda = \lambda_w/2 < 0.1$) are planimetrically unstable, tend to develop more intense width oscillations possibly leading the channel to bifurcate.

In meandering rivers two competing autogenic mechanisms are therefore predicted to compete in the temporal evolution of spatial width variations. These mechanisms act oppositely for "short" and "long" meander bends. Short bends (i.e. $\lambda > 0.2 \div 0.3$, cf. Figure 11) tend to have a stronger mid-channel bar component in the bed topography and therefore a higher tendency to symmetrically initiate spatial width oscillations. However these oscillations tend to be planimetrically stable according to the $\mathcal{O}(\delta)$ mechanism, which therefore competes against their temporal growth. It must be remarked that these considerations apply at the initial development stage of width oscillations and that the temporal dynamics of such competition cannot be quantitatively investigated within the present modelling framework. The reverse behavior is predicted for longer meander bends (i.e. $\lambda < 0.1$). The geometrical properties of spatial width oscillations of B_2, C, D or E meandering styles can partially reflect such opposite competition dynamics.

No single universal mechanism can be considered responsible for chutes initiation and stability in wider at bends meandering planforms (type D in Figure 12); rather these are recognized to result from either over-bar or over-bank incision, mid-channel bar growth or scroll-slough development [*Grenfell et al.*, 2011]. While the dynamics of chutes can be fully understood only accounting for both autogenic and allogenic processes, the role of the autogenic component on at least two of the controlling processes can be related to the predicted effects of width oscillations on bend instability - $\mathcal{O}(\nu\delta)$.

Chute initiation in large, sand-bed meandering rivers due to scroll-slough development has been shown by *Grenfell et al.* [2011] to occur more frequently at bends characterized by high lateral extension rates, which are predicted to increase under hydraulic conditions for which spatial width variations enhance linear bend instability. Chute formation associated with mid-channel bar growth [*Bridge et al.*, 1986], and possibly with over-bar incision can instead be put in relation with the opposite stabilizing effect of the mixed $\mathcal{O}(\nu\delta)$ response which similarly tends to reduce channel sinuosity with respect to hydraulically - equivalent equiwidth meanders. Finally, and in a much broader sense, the predicted development of multiple unstable longitudinal modes at the $\mathcal{O}(\nu\delta)$ can be viewed as a tendency to develop two almost equally unstable meandering channels with different wavelengths, whose geomorphic expression can be that of relatively stable "bifurcate" meander bends, as those with chutes common.

8. Concluding Remarks

The present work has aimed at quantitatively investigating the autogenic morphodynamic processes that shape the flow-bed topography fields in meandering channels with spatial width variations, viewed as representative of river patterns at the meandering-braiding transition. Three main research issues have been addressed. (1) The instream physical processes associated with meandering styles close to transition with braiding; (2) the cause-effect relationships associated with the contemporary presence of spatial curvature and width variations; (3) the possibility to investigate morphological differences between equiwidth and transitional meandering styles through physics-based, instream morphodynamic models.

The analysis has been developed through (i) a review of field observations and mathematical models relevant for meandering rivers with spatial width oscillations; (ii) a quantification of the properties of width variations in meanders relevant for modelling purposes; (iii) a unified, hierarchical derivation of models that are based on a perturbation approach and that allow association of different physical processes with the mathematical solution at each perturbation order; (iv) a review of the key model outcomes and comparison with the few available field and laboratory observations, integrated with some original model application; (v) a conceptual linkage between the model-predicted planform stability properties and descriptive classification of meandering channel patterns.

The depth-averaged model is solved through a comprehensive two-parameters perturbation approach. Results indicate that curvature-width interactions are fundamentally nonlinear: the hierarchical model structure allows to disentangle cause-effect relationships between width variations and mid-channel bars at the first nonlinear interaction.

In meanders with initially constant width, curvature nonlinearly forces mid-channel bar growth, promoting symmetrical bank erosion further downstream, thus being a possible trigger for width oscillations. These in turn can significantly affect meander stability and growth and therefore condition the curvature dynamics. Nonlinearities cause wider-at-bends meandering rivers to develop significantly shorter bends and to be morphologically more active with respect to constant width meanders. This picture is coherent with the relatively few available field observations.

The analysis is restricted to "autogenic" or "instream" processes, i.e. those occurring in the central flow region, where the boundary effects of banks can be ignored; bank processes are therefore only indirectly accounted for through a linear relationship between the near-bank excess velocity and the lateral channel migration rate. Despite this simplification, decades of meander modelling research have shown the potential of models relying on this assumption to capture relevant physical processes. It is unquestionable, however, that the full interaction dynamics between the river channel and the entire river corridor needs to be understood and modelled in order to build a more complete river-floodplain dynamics. This sets the scene for future research directions.

The array of biophysical processes and mutual interactions that need to be addressed can be conveniently illustrated moving from the central flow region to the vegetated floodplain patches, along an ideal cross-section of the whole river corridor. Among these, we deem that the following key ingredients deserve priority in future research.

1. The present review, namely in Sections 2 and 3, has highlighted the relative paucity of quantitative field data on spatial width variations in the various styles of meandering rivers, particularly close to the transition with braiding. Spatial and temporal width

variations can be quantified by fully exploiting the potential of remote sensing technologies and possible correlations with flow and sediment regime, catchment, floodplain and soil properties shall be assessed.

2. While flow dynamics in the central flow region has been extensively investigated, near-bank flow processes are still partially known, both for the eroding and for the accreting bank. Their knowledge is required for full coupling of bed-banks evolution. The growing scientific attention [*Güneralp et al.*, 2012] is presently biased towards processes near the eroding bank (*Kean and Smith* [2006], *Blanckaert and de Vriend* [2005]).

3. Evidence has been provided [*Lauer and Parker*, 2008] of local sediment imbalances in meandering rivers in association with bank erosion and channel curvature, with other field observations [*Gautier et al.*, 2007] indicating their morphodynamic relevance. Lateral sediment exchanges between the central flow region and the evolving banks have seldom been accounted for in meandering river models and potentially have fundamental implications for spatial and temporal width oscillations [*Chen and Duan*, 2006]. Morphodynamic coupling of banks and central flow regions through analytical models also show a bias towards the eroding bank, sometimes with great physical detail on processes causing collapse, failure and fluvial erosion [*Motta et al.*, 2012]. The modelling framework of *Parker et al.* [2011], accounts for the sediment imbalance through a laterally-integrated formulation of sediment continuity at both bank regions, thus allowing the eroding bank and depositing bank talk to each other and adjust the width of the central flow region in space and time. Coupling with analytical morphodynamic models for the central flow region [*Imran et al.*, 1999] has been only very recently attempted by *Eke and Parker*

[2011], coherently with the need to adopt a nonlinear model for the central flow region as suggested by the present review.

4. The eroding-bank-bias can be attributed to the largely more advanced understanding of bank erosion [*Rinaldi and Darby*, 2008] with respect to accretion [*Crosato*, 2008]. Consistent improvements in understanding and modelling the dynamics of bank accretion can be expected by accounting for flow unsteadiness and sediment heterogeneity [*Braudrick et al.*, 2009], which have seldom been incorporated in meander migration models (but see *Camporeale and Ridolfi* [2010]). The other key element controlling bank accretion are biotic-abiotic interactions associated with riparian vegetation dynamics [*Perucca et al.*, 2007], which plays a fundamental morphodynamic role in different types of river systems [*Gurnell et al.*, 2012] and is clearly recognized to made a difference in establishing single-thread and anabranching river channels on Earth [*Davies and Gibling*, 2011].

5. Descriptive classifications and rational predictors of channel pattern [*Kleinhans and van den Berg*, 2011] suggest the close association of chute cutoffs with meandering river styles at the transition with braiding (type D in Figure 12). Only recently significant progress towards quantitative understanding of their dynamics has been achieved from detailed analysis of field data (*Constantine et al.* [2009],*Micheli and Larsen* [2010], *Grenfell et al.* [2011]), while improvements in morphodynamic modelling of these "bifurcate meander bends" are still awaited. Coupled with field-based process understanding, this can decisively contribute to detect key differences along with more hidden similarities in processes typical of single- and multiple-thread alluvial streams.

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Figure 1. Illustrative examples of river morphologies across the continuum of alluvial channel patterns. (a) Meandering, Rio Yurua (Amazon region). Meandering with considerable spatial width variations: (b) Rio Beni (Bolivia); (c) Sacramento River (California, U.S.). (d) Braiding: Tagliamento River (Italy). Meandering patterns with width variations, mid-channel bars and chutes can be viewed as transitional forms between single- and multiple-thread patterns.

Figure 2. Modified Brice classification of single-thread alluvial river patterns. Classes have been grouped according to the absence or presence of spatial variations in channel width. Adapted from Lagasse et al. (2004).

Figure 3. Cumulative percentage of apex bend movement (a) and of dimensionless meander wavelength L^*/W^* (b) separately plotted for equiwidth (class B_1) and wider-at-bends (class C) meandering river bends of Brice classification. Based on Lagasse et al. (2004) and Luchi et al.(2011).

Table 1. Classification of existing mathematical models able to predict physical processes occurring in meandering rivers with spatial width variations.

	Model category	Reference	Time and spatial scales of application	Key issues in relation to paper subject
Analytical	(1) Instream morphodynamics in straight and meandering channels with spatial width variations and Partheniades-type lateral migration law	*Repetto et al.* [2002]; *Luchi et al.* [2010b]; *Luchi et al.* [2011]; *Luchi et al.* [2012]; *Frascati and Lanzoni* [2011]	Reach scale and wavelength scale, taken as representative of a longer reach with homogeneous hydro-morphological properties; flow-bed at equilibrium with the given planform	Explicitly address the separate role of the two planform forcings and their nonlinear interactions
Models	(2) Meander migration models with physics-based bank erosion migration and analytical flow-bed topography field	*Chen and Duan* [2006] *Motta et al.* [2012] *Parker et al.* [2011] *Eke and Parker* [2011]	Reach scale and wavelength scale, taken as representative of a longer reach with homogeneous hydro-morphological properties; flow-bed at equilibrium with the given planform; can simulate different relative timescales of bed and banks evolution	Focus on meander migration; emphasis on bank processes, mostly on erosion, with varying degrees of detail. Some incorporate lateral sediment exchange associated with banklines shift
Numerical	(3) Morphodynamic models with physics-based bank erosion and numerical flow-bed topography field	*Mosselman* [1992]; *Darby et al.* [2002]; *Jang and Shimizu* [2005]; *Rüther and Olsen* [2007];	Event-based or multiple formative events; reach scale (form one to some meander wavelengths). Suitable to simulate short-term planform evolution	Highly simplified description of bank accretion; difficult to systematically assess the separate roles of channel curvature and width variations in dependence of reach-averaged hydraulic conditions
Models	(4) Reduced - complexity models	*Coulthard and Wiel* [2006]; *Jagers* [2003]	Potentially suitable for long-term evolution of entire floodplain reaches because of smaller computational effort compared to fluid-mechanic based numerical models	Cellular and object based models. Potential for comparison with channel pattern prediction; physics is strongly simplified compared to other categories

Figure 4. (a) Image of a reach of the Rio Beni (Bolivia). (b) Channel width variations in the same reach. The width peaks almost invariably once per bend, regardless of bend orientation, suggesting that $L^* = 2L_w^*$. Capital letters $(A, ..., J)$ indicate inflection points.

Figure 5. Box plot illustrating the dimensionless amplitude δ of width variations (a) and ν of curvature variations (b) for C-class bends reported in the dataset of *Lagasse et al.* [2004]. The upper and lower limits of the grey boxes coincide with the 84^{th} and 16^{th} percentile respectively, with vertical lines extending to the 95^{th} and to the 5^{th} percentiles of the category. The percentage of river bends within the whole examined dataset for each class of λ is reported in brackets below the horizontal axis.

Figure 6. Sketch of a meandering channel with spatially variable channel width and notations employed in the mathematical model.

Figure 7. Typical asymmetric cross section in a meander bend, with opposite banks experiencing different processes, eventually resulting in local widening or narrowing. (data from River Bollin, UK; from Luchi et al., 2010

Figure 8. (a) Aerial view of the reach of the River Bollin (NW England) used for the application of the $\mathcal{O}(\nu^2)$ solution; the yellow bar indicates the cross section plotted in Figure 9b. (b,d) Downstream views of the same inflection region in April 2008 and July 2009 (courtesy of J. Hooke). (c) Relative position of the mid channel bar top $\eta_{20}^{(2)}(n=0)$ and of the peak of the related symmetrical perturbation of the longitudinal velocity $U_{20}^{(2)}$ at the banks ($\beta = 6.21, \tau_* = 0.06, d_s = 0.03$). The yellow bar indicates the position of the cross section where the mid-channel bar top has been observed along half meander wavelength.

Figure 9. (a) Representative cross sections at meander inflection in the reach of the River Bollin investigated by Luchi et al. (2009c). (b) Conceptual explanation of the topographically-driven mechanism for the generation of width variations in a meandering channel.

Figure 10. (a) Marginal bend stability curves in the $\lambda - \beta$ parameter space for different intensities δ of spatial width variations ($\tau_* = 0.1, d_s = 0.08, \omega = 0$). (b) Comparison between the wavenumber selected by the classical linear bend theory ($\mathcal{O}(\nu)$, see Section 4.2) and the wavenumber of low sinuosity stream reaches extracted from the dataset of Hey and Thorne (1986).

Figure 11. (a) Ratio of the amplitudes of the mid-channel bar ($\mathcal{O}(\nu^2)$) and point bar ($\mathcal{O}(\nu)$) components of bed topography in the experimental runs of *Colombini et al.* [1991] (open circles) and predicted by the reviewed models for the same hydraulic and geometric conditions (closed circles). Input parameters ranges: β ($11 \div 22$); τ_* ($0.04 \div 0.07$); d_s ($0.05 \div 0.09$); based on *Luchi et al.* [2010b]. (b) Predicted meander bend growth rate for equiwidth ($\mathcal{O}(\nu)$, continuous line) and wider at bends ($\mathcal{O}(\nu) + \mathcal{O}(\nu\delta)$, dashed line) $\tau_* = 0.08$; $d_s = 0.04; \beta = 20; \delta = 0.17$. Based on *Luchi et al.* [2011].

Laterally asymmetrical mechanism	*Laterally symmetrical mechanism*
one bank in erosion, the opposite bank in accretion	both banks in erosion
width variations have a *forcing* function with respect to mid-channel bars	width variations have a *following* function with respect to mid-channel bars
mid-channel bars are a *linear* topographical response	mid-channel bars are a *nonlinear* topographical response

Table 2. Comparison between the two mechanisms proposed to explain the occurrence of spatial width variations in meandering channels.

Figure 12. A process-form diagram of width - curvature interactions in equiwidth and transitional meanders based on a two-parameters perturbation approach. The left column qualitatively illustrates the planform, flow and bed topography pattern corresponding to each perturbation order. The Brice meander pattern classification, partially redrawn in the right column, is put in relationship with the planform stability properties of each perturbation order.