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Dynamics of river meanders:
bankfull geometry and planimetric configuration

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LIST OF SYMBOLS AND ABBREVIATIONS

B	half width
C_f	friction coefficient
C'_f	friction coefficient for the skin friction contribution
C''_f	friction coefficient for the form drag contribution
C_{fD}	relative variation of the friction coefficient with the water depth
C_{fT}	relative variation of the friction coefficient with the Shields parameter
D	depth
D'	boundary layer thickness
E	erodibility coefficient
F_r	Froude number
H	free surface elevation
L	intrinsic length of the channel axis
L_x	Cartesian length
Q	discharge
Q_s	sediment discharge
R	curvature radius
R_T	ratio between the planimetric and bed evolution timescales
R_p	Reynolds' particle number
S	river bed slope
T_b	timescale for the bed evolution
T_f	timescale for the planimetric evolution
U	longitudinal velocity

V transverse velocity
 Δ relative submerged density of sediments
 Φ sediment transport function
 Φ_D relative variation of the sediment transport function with the water depth
 Φ_T relative variation of the sediment transport function with the Shields parameter
 β aspect ratio
 β_R resonant aspect ratio
 δ amplitude of width oscillation
 η river bed elevation
 λ meander wavenumber
 λ_m meander wavenumber for the m -harmonic
 $\lambda_{m,j}$ characteristic exponents for the solution of Equation 72
 $\mathcal{C}$ curvature
 ν water kinematic viscosity
 ν_0 reference non-dimensional curvature
 ν_{bend} curvature ratio of the bend
 ψ bend skewing angle
 ρ water density
 σ total sinuosity
 σ_{bend} bend sinuosity
 τ shear stress
 τ_* Shields parameter
 τ'_* skin friction contribution for the Shields parameter
 τ''_* form drag contribution for the Shields parameter
 τ_{*cr} critical value of the Shields parameter
 θ angle between the tangent to the centreline and the x-axis
 ζ migration rate

$c.c.$ complex conjugate

c_{mj} coefficients for the boundary conditions in the ZS solution

d_s relative roughness

d_{g50} median sediment grain size

g gravitational acceleration

m harmonic number

n transverse coordinate in the curvilinear Cartesian reference system

p_b bed porosity

p_f floodplain porosity

s longitudinal coordinate in the curvilinear Cartesian reference system

t time

x coordinate aligned with the main direction of the floodplain in the orthogonal Cartesian reference system

y coordinate across the floodplain in the orthogonal Cartesian reference system

z vertical coordinate

ADCP Acoustic Doppler Current Profiler

GEE Google Earth Engine

GNSS Global Navigation Satellite System

iWBMS Wideband Multibeam Sonar

LSU Louisiana State University

MBES MultiBeam Echo Sounders

MCMM Meander Centreline Migration Model

MNDWI Modified Normalized Difference Water Index

MT approach Monegaglia and Tubino (2019) approach

NDVI Normalized Difference Vegetation Index

PyRIS Python-Rivers from Satellite

SWIR Short Wave InfraRed Band

USACE US Army Corps of Engineers

USDA-ARS USDA-Agricultural Research Service

VMT Velocity Mapping Toolbox

XS cross-section

XSs cross-sections

ZS Zolezzi and Seminara (2001)

ABSTRACT

Meandering rivers are ubiquitous on the surface of the Earth and are key elements of every ecosystem they are embedded in. They distribute water, sediments and nutrients all over the floodplain, they provide a mean of transportation and energy production, and they offer many other ecosystem services that are vital for the flora, the fauna and the communities living close to them. However, even in the most remote areas of the world, meandering rivers are impacted more and more by climate change and by human activities, such as damming, agriculture, and mining. For these reasons, multiple studies were focused on the analysis of the dynamic behaviour of meandering rivers. However, there has been little development of models aimed to simulate the effects of these forcings on the long term evolution of meandering rivers. The aim of my PhD project is to understand how these external stressors affect the bankfull geometry and the planimetric configuration of meandering rivers.

To achieve this goal, in this PhD thesis I combined various modelling tools, with satellite data and field measurements. I first focused the analysis on the relationship between the bankfull geometry and the morphometric properties of meanders, by means of the semi-analytical evolutionary model developed by Bogoni et al. (2017). The analysis revealed a strong influence of the bankfull geometry on the planimetric configuration of meanders. In particular, the distance from the resonant condition, which can be viewed as a combined metric depending on the bankfull geometry, showed the largest differences in the morphometric properties, such as the bend skewing angle, and the bend and total sinuosity, thus providing a suitable tool to predict the long-term behaviour of a meandering river for different combination of the external parameters (e.g. flow and sediment inputs, valley slope, grain size). To exploit it, I specifically developed a simple model that predicts the evolution of the bankfull geometry with changing sediment supply, distinguishing sand and gravel bed rivers.

Conversely, comparing model results with satellite imagery data revealed that the simulations tend to overestimate the observed total sinuosity of meanders. Furthermore, it pointed out the inability of the model to represent the effects of changes in water and sediment regime, and consequently to properly model the effects of external stressors. To overcome the latter shortcoming, I developed a simplified multi-reach model based on the approach recently proposed by Monegaglia and Tubino (2019), aimed at a more physically based description of the adaptation of meander bankfull geometry to planform changes. The new approach introduces a local update of the bankfull geometry parameters based on the effects of the changing sediment supply on the river bed slope. The capability of modelling the effects of changes in the sediment supply provides a powerful tool to describe the effects of external stressors. In the framework of this analysis, during a two-month visiting period at the Louisiana State University in the US, I collected flow field and bathymetric data on the Sabine River in a field survey. The ultimate goal was to characterize a meandering river stretch that exhibits a distinctive change of bankfull properties between adjacent reaches. Field observations also highlighted the existence of flow recirculation zones in high curvature bends, which protect the river banks from erosion and therefore inhibit a further increase in channel sinuosity. Their effect is not accounted for in present models, which may explain why they tend to overestimate channel elongation. Therefore, a suitable quantification of their role could lead to a more accurate bank erosion predictor.

Finally, I focused my attention on the particular features of river flowing in permafrost covered floodplains. I compared the morphometric properties of these rivers with rivers in a temperate and tropical settings using satellite imagery. I found a more pronounced width variability in permafrost rivers, which can be related to the erosion dynamics of the glaciated bank. This precarious equilibrium could be easily disrupted by the effects of climate change and so it is relevant that these environments are further investigated to understand the underlying processes.

In conclusion, the results of my PhD project shed some light on the often overlooked

connection between the bankfull geometry and the long-term planimetric configuration of meandering rivers, and provide insight into the effect of external stressors on their evolution. Moreover, the proposed approach lays the foundation for a novel set of models for the long term evolution of meandering rivers, able to reproduce the changing condition that these rivers are facing.

CHAPTER 1. INTRODUCTION

1.1 The nature and behaviour of meandering rivers

Meandering rivers are ubiquitous in every environment of the Earth surface, from deep into the Amazon forest (Gautier et al., 2007) to the permafrost covered areas in the Arctic regions (Ragno et al., 2024). They develop in sandy floodplains, but also on glaciers and even turbidity currents form meandering channels (Seminara, 2006). They show a variety of shapes and sizes and the regularity of the long stretches of alternating bends has always struck the man imagination. Starting from mentions in the Greek mythology and by Roman historians, passing through the keen eye for details of Leonardo da Vinci (Seminara et al., 2023a), meandering rivers have always been studied and observed. Even if the beauty of meandering rivers has definitely played a role in the fascination of humans for them, their presence has always been of the utmost relevance in every ecosystem and society they are a part, as for instance in the case of the Nile (Hughes, 1992).

The distinctive shape of meandering rivers is the result of a complex combination of phenomena. On one side, the channel curvature forces the flow of water and sediments, and the bed topography (Seminara, 2006), leading to erosion of the outer bank and deposition in the inner bank (Parker et al., 2011; Thorne, 1991). These erosion and deposition patterns promote the elongation and migration of the bends, increasing the sinuosity and the curvature of the river. Conversely, meandering rivers shorten through the cutoff process (Camporeale et al., 2008), which counteracts the aforementioned elongation, leading to a dynamic equilibrium of the reach sinuosity (Camporeale et al., 2005). Regardless of the type, which will be described in chapter 2, cutoffs are often set off by particular hydrological conditions, as flood events, and often the disturbance caused by the occurrence of a cutoff induces a series of others (Gautier et al., 2007; Hooke, 2004), shortening the length

of the river even more. While this two-fold dynamic explains part of the phenomenology of meandering rivers, it is not sufficient to describe fully the behaviour of meandering rivers. The cohesion and erodibility of the floodplain and bank material have a key role in the erosion process (Bogoni et al., 2017; Güneralp & Rhoads, 2011; Thorne, 1991) and the vegetation has also a significant effect for the bank stabilization (Perucca et al., 2007). In particular, the presence of vegetation (Gran & Paola, 2001; van Dijk, Teske, et al., 2013) or the intermittent introduction of cohesive sediments (van Dijk, van de Lageweg, & Kleinhans, 2013) has allowed the meandering patterns to be maintained in laboratory experiments, and so the bank cohesion and the effects of vegetation has been linked to the very existence of meandering rivers. Moreover, the behaviour of meandering rivers is also complicated by bedform migration, such as migrating bars (Monegaglia et al., 2018), width variability (Zolezzi, Luchi, & Tubino, 2009), linked to particular conditions of the flow (Zolezzi et al., 2012) or to the floodplain heterogeneity (Ragno et al., 2024).

1.2 Effects of external stressors on meandering rivers

These intricate and beautiful systems have been manipulated by humans for ages for navigational purposes (Tibbs & Campbell, 2024), for agricultural enhancement (Hughes, 1992) and for flood protection (Buer et al., 1989). In more recent years, extensive damming for water storage and hydropower production has affected rivers in densely populated areas (Phillips, 2003; Zolezzi, Bellin, et al., 2009), but even more remote areas are not immune from the human hand (Marren et al., 2014; Salerno et al., 2022). Land use changes (Ielpi et al., 2022) have also played a role in the significant alterations of the hydrological and sediment regime (Parker & Török, 2023). Moreover, the effects of climate change are also evident when looking at the behaviour of meandering rivers (Guerrero et al., 2013), as, for example, a changing migration rate due to the permafrost thawing (Ielpi et al., 2023).

All these changes affect profoundly the rivers bankfull geometry, planimetric configuration and behaviour (Crivellaro, Serrao, et al., 2024; Surian & Rinaldi, 2003) and can

have an impact on the ecosystems they are a part of. However, due to the long timescales of evolution of meandering rivers (Frascati & Lanzoni, 2009), the effects of changes in meandering rivers can take decades to show and to fully develop. Thus, predicting how these alterations ultimately change the morphological trajectories of meandering rivers is key to understand the impacts of human activities on the environment they flow through and how to counteract their consequences, such as bed degradation, channel narrowing and reduction of the morphological activity (Crivellaro, Serrao, et al., 2024; Phillips, 2003, 2008; Salerno et al., 2022; Surian & Rinaldi, 2003), before they arise.

1.3 Investigating meandering rivers

Since the interest for the behaviour of meandering rivers has lasted for a long time, they have been studied with a variety of different methods, which could be also employed to analyse the effects of these external stressors. Among the pioneering works of the last century, the simple description of the meander shape with the sine-generated curve proposed by Langbein and Leopold (1964) and Kinoshita (1961), and the seminal work of Rozovskii (1957) stand out. The latter was key in the description of the effects of the curvature of the river on the flow field, while the former were able to describe the intrinsic periodicity of meandering rivers, even introducing terms to better approximate the complex shapes of meander bends in the case of Kinoshita (1961), that were later recognized as geometrical non-linearities (Seminara et al., 2001).

As for other riverine processes, meandering rivers have been studied with several approaches providing complementary data. Laboratory experiments have given incredible insights on the key feature of the flow field and bed topography of meandering rivers, such as the upstream morphodynamic influence (Struiksma et al., 1985; Zolezzi et al., 2005), the properties of the flow field (Blanckaert, 2010, 2011; Blanckaert & De Vriend, 2004; Blanckaert & Graf, 2004), and the effect of vegetation (Gran & Paola, 2001; van Dijk, Teske, et al., 2013) or cohesive sediments (van Dijk, van de Lageweg, & Kleinhans, 2013)

on the planform configuration. Field measurements have been widely used to understand the distribution of the bankfull geometry (Lagasse et al., 2004), to describe the cutoffs and post-cutoff behaviour (Gautier et al., 2007; Konsoer et al., 2016; Richards & Konsoer, 2020; Richards et al., 2022), to understand peculiar flow conditions and bed topography configurations (Abad et al., 2023; Deng et al., 2021; Vermeulen et al., 2014), and to estimate the solid and liquid discharges (Amsler & Drago, 2009; Latrubesse et al., 2005). In the last decades, remote sensing has taken hold as one of the preferred tool to investigate the dynamics of rivers, and meandering streams are no exception to this trend (Constantine et al., 2014; Guo et al., 2019; Monegaglia et al., 2018; Ragno et al., 2024; Rowland et al., 2023; Salerno et al., 2022; Schwenk et al., 2017; Speed et al., 2024; Sylvester et al., 2019; Vermeulen et al., 2016; Zolezzi & Güneralp, 2016). Satellite data allow for the evaluation of the planimetric properties of rivers, particularly, in remote areas, where they are often almost untouched by human activities. Moreover, they span now on just over forty years of data collection, giving the ability to evaluate accurately also the time evolution of meanders.

While being almost necessary to understand meandering rivers, these techniques show some intrinsic limitation that using modelling approaches can overcome. For instance, field and laboratory do provide a complete description on the river flow field, bathymetry, bed composition and other relevant properties, but they are representative of that particular river, condition and stage and are quite time-consuming to collect and process. On the other hand, satellite data allow for longer time span of survey, but they give only limited information on the bankfull geometry and the property of the floodplain. However, models can describe the long term evolution of meandering rivers, both in terms of bankfull geometry and planimetric configurations and they are key tools in the investigation of meandering rivers (Frascati & Lanzoni, 2009).

Linear models have been used for decades (Blondeaux & Seminara, 1985; Camporeale et al., 2007; Crosato, 1990; Garcia et al., 1994; Howard, 1996; Howard & Knutson, 1984;

Ikeda et al., 1981; Johannesson & Parker, 1989; Motta et al., 2012) to investigate the key processes of meandering rivers, such as the bi-dimensional morphodynamic influence (Zolezzi & Seminara, 2001) and the nature of the bend instability (Lanzoni & Seminara, 2006; Seminara, 2006), or the effects of heterogeneity in the floodplain material (Bogoni et al., 2017; Güneralp & Rhoads, 2011). However, due to the strong simplifications of the linear solutions, various researchers have extended the model to include higher order effects (Blanckaert & de Vriend, 2010; Bolla Pittaluga & Seminara, 2011; Bolla Pittaluga et al., 2009; Ottevanger et al., 2013; Seminara & Solari, 1998), as, for example, to describe the behaviour of the flow field close to the resonant condition (Seminara & Tubino, 1989, 1992). Moreover, further developments have introduced the effects of the varying width, with a linear model (Frascati & Lanzoni, 2013; Repetto et al., 2002; Zen et al., 2014), analysing the interaction between the width and curvature forcings (Luchi et al., 2011, 2012; Zolezzi et al., 2012), and studying its genesis (Monegaglia et al., 2019). Lastly, other researchers proposed approaches including numerical modelling (Asahi et al., 2013), more comprehensive descriptions of the bank erosion (Parker et al., 2011; Viparelli & Eke, 2021) or focusing in general on the evolution of the bankfull geometry of meandering rivers (Eke, Czapiga, et al., 2014; Eke, Parker, & Shimizu, 2014; Li et al., 2015; Monegaglia & Tubino, 2019).

However, modelling approaches have still room for improvements. For starters, the bankfull geometry has often been left in the background to focus on the planimetric configuration, when using the linear models. However, as it will be clear along this PhD thesis, the connection between the two has significant ramification on their evolution. Moreover, these models often use a spatially constant base flow, which leads to the inability of the model to represent the individual bend dynamics, keeping the same regime for the entire reach. However, during their evolution, bends are often found transitioning between the super- and sub-resonant regime (Guo et al., 2019; Zolezzi, Luchi, & Tubino, 2009). On top of that, the width evolution, the bank erosion and the cutoff occurrence could be better

parametrized, in order to reduce the total sinuosity of the planimetry and to better describe the meander migration under different floodplain characteristic, as for instance permafrost cover. Lastly, only a few works focused on the impacts of external stressors on meandering river (Salerno et al., 2022, 2023) and, in particular, only a few focused on the effects of changes in the solid or liquid discharge on the bankfull geometry and planimetric configuration of meandering rivers (Naito & Parker, 2019, 2020). However, some of the currently available models could be combined and utilized to overcome these limitations and, in particular, they could be used to simulate the long term evolution of meandering rivers under external forcings.

1.4 Aim and structure of the thesis

In this dissertation I aim to investigate the relationship between the bankfull geometry and the planimetric configuration of meandering rivers, together with the effects of external forcings on their dynamics. To do so, I will firstly focus on the connection between the bankfull geometry and the planimetric configuration through the use of a linear model. I will compare these results against satellite data, to understand the limitations of the model in the depiction of the bend behaviour. I will then use the relationship between the bankfull geometry and the planimetric configuration to develop a simple tool able to describe the effects of external forcings on the equilibrium bankfull geometry. A new bend-based bankfull geometry update will be developed, which I will use to describe the influence of an evolving bend on the neighbouring ones and to introduce the one-dimensional morphodynamic influence, which connects the sediment supply and the timescale of evolution of the river bed to the adjustment to an imbalance of the bankfull geometry. The field data collected during my two-month abroad period at Louisiana State University (LSU) in the United States will be used to compare the results of the local updates of the bankfull geometry with the behaviour of different reaches of the Sabine River. Lastly, I will present the results of a satellite analysis on the effects of permafrost cover in the floodplain, dis-

cussing a few potential solutions for the simulation of different environments and different bank erosion behaviours. As stated above, this combination of existing and new modelling approaches, and satellite and field data, will be indispensable for the analysis of the future evolution of meandering rivers in this changing world. The ultimate objective of these tools is the prediction of meandering rivers future dynamics that could help river managers and public agencies to preserve mostly natural or natural-like riverine ecosystem, before they follow the step of other more anthropized counterparts (Parrinello et al., 2021).

After this introductory chapter, the thesis will be structured as follows. In chapter 2 I will introduce the notation, models, tools and data used in this thesis. In chapter 3 I will present and discuss the results of the analysis on meandering rivers. Finally, in chapter 4 I will draw the conclusions of this PhD work and present some of the future perspectives to continue the development of our knowledge on meandering rivers.

CHAPTER 2. MATERIALS AND METHODS

In this chapter I introduce the tools used for the analyses performed in chapter 3. In particular, I present the basic equations and the models adopted for investigating the long term evolution of meandering rivers in section 2.1, while in section 2.2, I report the tools used for the analysis of satellite data, and finally, in section 2.3, I detail the datasets used for comparisons of the model results with field data, which are the Lagasse et al. (2004) database and the data collected on the Sabine River during this PhD program.

2.1 Equations and models for meandering rivers

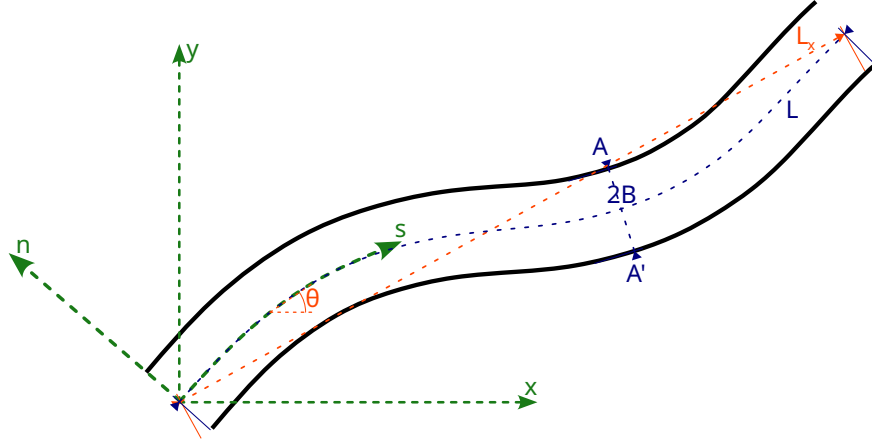
Meandering rivers often evolve slowly, in a far longer timescale that what can be observed with field data, and for that reason modelling has always been a key tool to describe their behaviour (Frascati & Lanzoni, 2009). In this PhD work various modelling approaches have been the core of the analyses carried out and here they are detailed, starting from the equations from where the models are derived.

2.1.1 *Notation and parameters*

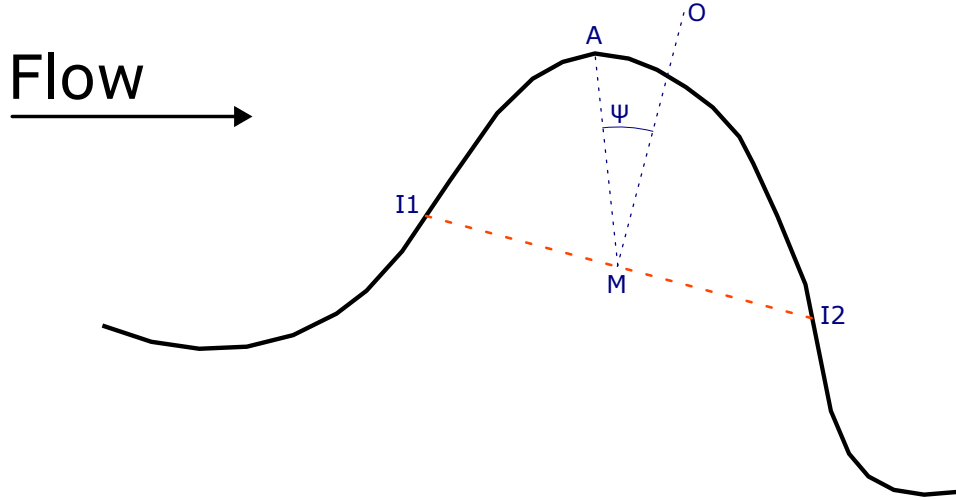
To facilitate the reader, here is reported a brief description of the geometric notation and parameters used for meandering rivers. Firstly, the quantities denoted by a * superscript are dimensional quantities, while the one without it are non-dimensional quantities; the quantities denoted by a ₀ subscript are the reference value for that particular variable, which can change depending on the specific topic analysed. In Figure 1, an example of the planimetric and bend configurations of a meandering river with its notation. As it is plotted in Figure 1a, there are two different reference system used with meandering rivers:

- a Cartesian orthogonal reference system, with x oriented along the main direction of the floodplain and y across it;

- a Cartesian curvilinear reference system, with s as coordinate along the river centre-line and n as transverse coordinate across the cross-section (XS).



(a) *Planimetric configuration*



(b) *Bend configuration*

Figure 1 – Example of planimetric (a) and bend (b) configurations for a meandering river. In (a) are indicated the axis (s and n) for the Cartesian curvilinear reference system and the axis (x and y) for the Cartesian orthogonal reference system. Moreover, intrinsic length of the channel axis (L) and its Cartesian length (L_x) are represented respectively in blue and orange; the angle between the tangent to the centreline and the x -axis (θ) is drawn in orange and the cross-section (XS) AA' , depicted in Figure 4, is displayed in blue and it is $2B$ wide. In (b) are indicated the bend apex A , the inflection points $I1$ and $I2$, the middle point M of the conjoining line between $I1$ and $I2$ and the point O on the perpendicular line to $\overline{I1I2}$, which are all used to define the bend skewing angle (ψ).

The vertical coordinate (z) is the same for both reference system and it is oriented in

the opposite direction of the gravitational acceleration (g), as it is shown in Figure 4. The planimetric configuration of meandering rivers can be described with a few parameters, which are a combination of the half width (B), the curvature radius (R), the angle between the tangent to the centreline and the x-axis (θ), the intrinsic length of the channel axis (L) and its Cartesian length (L_x). One of the most important parameters in a meandering river is the curvature ($\mathcal{C}$), which is the inverse of the curvature radius, but it can also be defined as

$$\mathcal{C} = -\frac{d\theta}{ds}. \quad (1)$$

The reference non-dimensional curvature (ν_0) is defined as the ratio between a reference value of B and the minimum value of R , reading

$$\nu_0 = \frac{B_0^*}{R_0^*} \quad (2)$$

and it is $\mathcal{C}$ maximum value.

Since meandering rivers show a readily apparent periodicity, they have often been described with a sine-generated curve, as proposed by Langbein and Leopold (1964). Since meandering rivers can be treated as waves, the meander wavenumber (λ) is often used and can be defined as

$$\lambda = \frac{2\pi B^*}{2L_{\text{bend}}^*}, \quad (3)$$

with the length of the bend (L_{bend}^*) being the length of the axis between two inflection point $I1$ and $I2$. The inflection points are commonly used as extremities of a bend and are located where the axis curvature changes sign, $I1$ and $I2$ in Figure 1b. While the description proposed by Langbein and Leopold (1964) reminds a meander bends, the bends are generally far from a perfect sine-generated curve and they display various degrees of non-linearities. Kinoshita (1961) proposed a more complete description of the $\mathcal{C}$ to encompass these non-linearities updating the sine-generated formulations by including the fattening and skewing

coefficients. The Kinoshita (1961) formulation reads

$$\mathcal{C}^* = \mathcal{C}_0^* (\cos(\lambda^* s^*) - \mathcal{C}_F \cos(3\lambda^* s^*) - \mathcal{C}_S \sin(3\lambda^* s^*)). \quad (4)$$

In his equations, one of the key aspect is the third order that characterizes non-linearities, which will be relevant in section 2.1.3.1.

To represent the complexity of the planimetric configuration of a river the total sinuosity (σ) is used, defined combining the intrinsic and Cartesian length of the entire river as

$$\sigma = \frac{L^*}{L_x^*}. \quad (5)$$

When the same definition is applied to a single bend, using the intrinsic and Cartesian length between the bend inflection points, the bend sinuosity (σ_{bend}) is obtained. To further describe the shape of a meander bend, the bend skewing angle (ψ) is used, to show if the bend is pointing against the flow direction (upstream skewed) or with the flow direction (downstream skewed). If the inflection points are connected with the $\overline{I1I2}$ segment, the ψ can be defined as the angle between the segment $\overline{MA}$ and $\overline{MO}$, respectively connecting the middle point M to the bend apex A and to a point O on the perpendicular line to $\overline{I1I2}$. ψ is considered positive when the bend is skewed downstream and negative if its skewed upstream, as in the example in Figure 1b. The difference between upstream and downstream skewed bends can be seen in Figure 7.

Lastly, to describe the width variability of bends, the amplitude of width oscillation (δ) is used and it can be defined using a combination of the maximum width (B_{max}^*) and its reference value (B_0^*) as

$$\delta = \frac{B_{max}^* - B_0^*}{2B_0^*}. \quad (6)$$

2.1.2 *Model formulation*

There are several models developed along the years to study the long term evolution of meandering rivers (Bogoni et al., 2017; Camporeale et al., 2007; Crosato, 1990; Eke, Czapiga, et al., 2014; Eke, Parker, & Shimizu, 2014; Frascati & Lanzoni, 2010, 2013; Garcia et al., 1994; Ikeda et al., 1981; Johannesson & Parker, 1989; Motta et al., 2012; Parker et al., 2011; Seminara et al., 2001) and in general every model has a few main ingredients (Crosato, 1990):

- a flow field and bed topography solution,
- a centreline evolutionary model,
- a baseflow evolution model.

In this section some of the different approaches used will be described for each of these ingredients and then the model used through this PhD work will be introduced briefly in section 2.1.6. While the aforementioned ingredients are ordered with the logic they are generally implemented in the models, their design starts from the centreline evolutionary model, which will be described first.

2.1.3 *Centreline evolutionary model*

Meandering rivers move and evolve constantly without showing any sign of a fixed equilibrium. However, Camporeale et al. (2005) proved the existence of a dynamic equilibrium, which is maintained via a two-fold process. The river slowly and constantly elongates up until a cutoff happens shortening it abruptly, creating what it is called statistical steady state. An appropriate description of both ingredients is necessary to fully describe the evolution of meandering rivers.

2.1.3.1 Bank erosion law

The elongation is generally described with a convoluted mix of erosion of the outer bank (bank pull) and deposition at the inner bank (bar push) of each bend (Seminara, 2006). The bank pull process is typically detailed as a complex phenomenon that consists of erosion of the bank toe, with the consequent collapse of the more cohesive top layer. The collapsed slump blocks then protect the bank until they are removed by the flow. The flow moves the material and deposits it on the inner banks making the point bar grow (Parker et al., 2011). Since the residence of this material in the basal zone of the bank is only governed by the flow, Thorne (1991) defines this phenomenon as basal endpoint control, describing how this ability to erode and deposit is only related to the flow capability of removing sediments. For this reason, several bank erosion laws were designed to take into account only some flow field properties when describing the migration of the channel. Among this various erosion laws, one of the most used is the one described by Ikeda et al. (1981) and Hasegawa (1977), which derives from the work of Partheniades and Paaswell (1970). The migration rate (ζ) described as a function of the difference between the inner and outer bank velocity U multiplied by an erodibility coefficient (E). The formulation proposed by Seminara et al. (2001) reads

$$\zeta = E (U|_{n=+1} - U|_{n=-1}) \quad (7)$$

with n the transverse coordinate scaled with a representative value of the B , which goes from -1 for the left bank to +1 for the right bank. Seminara et al. (2001) argue that the velocity is not necessarily the parameter which better represents the actual process, as for instance Blondeaux and Seminara (1985) used the shear stress, which is much closer to the physics of the phenomena. However, Seminara et al. (2001) tested the sensitivity of the solution with different options and they did not find a difference in the behaviour of the model with other flow parameters.

Equation 7 is sufficient to evaluate the evolution of a river numerically, as it was implemented for instance in the model developed by Bogoni et al. (2017). However, using a simple geometric projection of the ζ is possible to derive a simple expression that describes directly the shape of the meandering river during its migration. Ikeda et al. (1981) proposed a simple equation reading

$$\frac{\partial \bar{y}}{\partial t} \cos(\theta) = \zeta \quad (8)$$

with $\bar{y}$ being the position of a point of the axis.

Seminara et al. (2001) further refined this approach using a more complete geometric representation found in Figure 2.

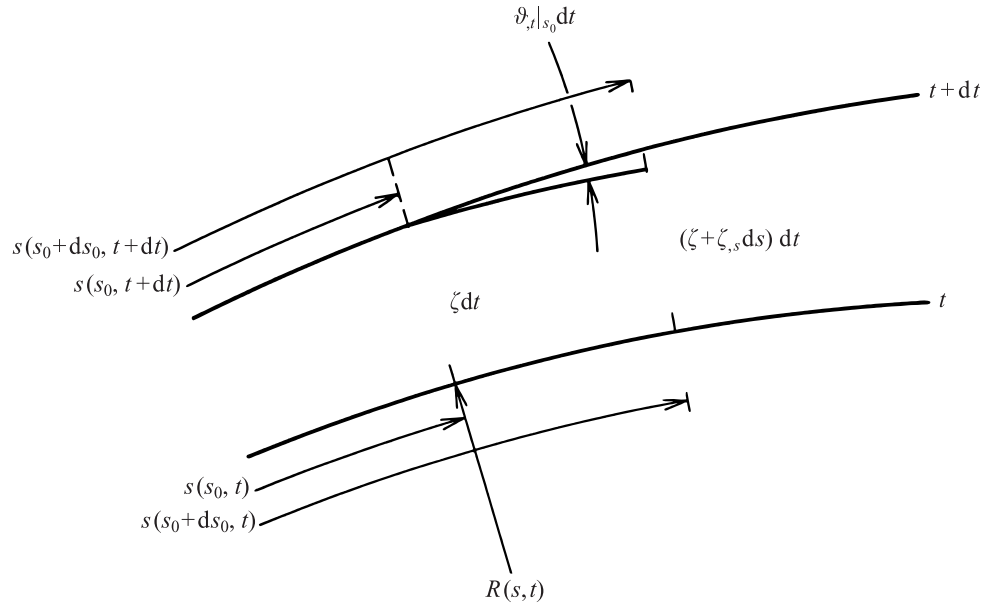


Figure 2 – Geometric scheme used by Seminara et al. (2001) to derive the equation for the evolution of the angle between the tangent to the centreline and the x-axis (θ) in time.

The derivation starts with the analysis of the transverse variation in the position of a point of the centreline of coordinate s and a point of coordinate $s + ds$ in a time dt . When the two are subtracted, the difference amounts to

$$\left(\zeta + \frac{\partial \zeta}{\partial s} ds - \zeta \right) dt = \frac{\partial \zeta}{\partial s} ds dt = \left(\frac{d\theta}{dt} dt \right) ds \quad (9)$$

and it is equal to the total variation of θ in the same time interval. When the equation is transformed from Lagrangian to Eulerian it becomes

$$\frac{\partial \theta}{\partial t} + \frac{\partial \zeta}{\partial s} \frac{ds}{dt} = \frac{\partial \zeta}{\partial s}. \quad (10)$$

In a dt time interval the length of the ds segment changes of a $d(ds)$ amount, that can be calculated as

$$d(ds) = \frac{\zeta dt}{R} ds = -\zeta \frac{\partial \theta}{\partial s} ds dt. \quad (11)$$

Knowing that $\mathcal{C}$ is 1 over R and it can be described as seen in Equation 1, the term $\frac{ds}{dt}$ can then be calculated as

$$\frac{ds}{dt} = - \int_0^s \zeta \frac{\partial \theta}{\partial s} ds. \quad (12)$$

Substituting this term in Equation 10 the final equation is obtained and it reads

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial s} \int_0^s \zeta \frac{\partial \theta}{\partial s} ds = \frac{\partial \zeta}{\partial s}. \quad (13)$$

This equation, derived by simple geometric considerations, allows for the description of the evolution of the θ in time (t). Its non-linearities arise from purely geometric constraints, no matter the formulation of ζ . Moreover, the non-linearities are of the third order, just like in the Kinoshita (1961) formulation presented in Equation 4.

Equation 13 has been used to develop an exact solution for the evolution of meandering rivers in the periodic case that will be discussed in section 2.1.4.4 after introducing the appropriate periodic solution for the flow field. Equation 7 will be used instead with a flow field solution for an arbitrary distribution of curvature, to evaluate the evolution of rivers with shapes closer to the real meanders.

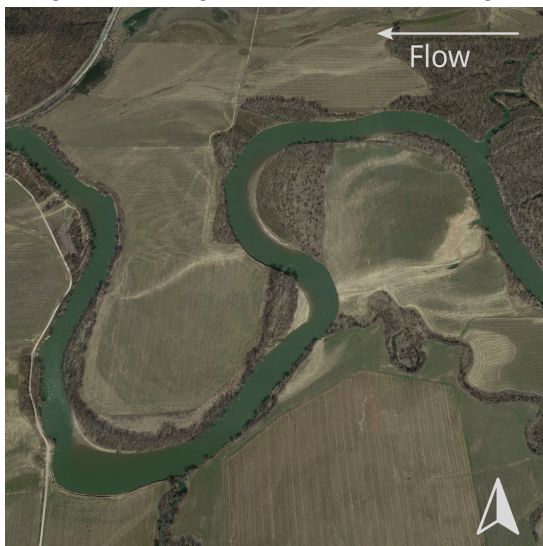
2.1.3.2 Cutoffs



(a) Neck cutoff - Rio Beni 2013 (Bolivia)
Google Earth Image ©2024 Maxar Technologies



(b) Neck cutoff - Rio Beni 2020 (Bolivia)
Google Earth Image ©2024 Maxar Technologies



(c) Chute cutoff - East Fork White River 2013 (US)
Google Earth Image ©Landsat / Copernicus



(d) Chute cutoff - East Fork White River 2024 (US)
Google Earth Image ©2024 Airbus

Figure 3 – Examples of neck (a-b) and chute (c-d) cutoffs happening respectively in the Rio Beni (Bolivia) and in the East Fork White River (US). In the Rio Beni there are two neck cutoffs happening more or less at the same time. In the East Fork White River the two chute cutoffs are still at an early stage, but the new channel is stabilizing and it could lead to two complete avulsions of the old branches in the following years.

Cutoffs shorten a river when the bends are becoming too sinuous. There are two main different types of cutoffs, namely:

- neck cutoffs, like in Figures 3a and 3b, which happen when the channel come in contact with itself;
- chute cutoffs, like in Figures 3c and 3d, which happens when the river creates a new channel that bypass the older one.

Usually, the former happens on higher sinuosity rivers, while the latter happens in lower sinuosity streams. They are often both associated with floods event (Gautier et al., 2007; Hooke, 2004). However, neck cutoffs generally migrate until the two branches are touching and only need a flood event to cut the bank and connect the two channels. On the other hand, chute cutoffs generally need several flood events to overflow and to create the new channel.

Generally, when modelling of meandering river evolution, neck cutoff are easily described (Bogoni et al., 2017; Camporeale et al., 2007, 2008; Frascati & Lanzoni, 2009; Lanzoni & Seminara, 2006), while chute cutoff are more complex, since they would need a thorough investigation of the properties of the point bar, the vegetation, the floodplain and of the hydrological variability (Camporeale et al., 2008). Only a few researchers (Howard, 1996; Liverpool & Edwards, 1995) tried to include the process in a modelling approach, but the problem remains open. Theoretically, chute cutoffs could be correlated with the water depth calculated with the flow field solution, but this would entail rethinking completely the bank erosion law used and described earlier.

2.1.4 Flow field and bed topography solution

As it is clear from Equation 7, the key element in describing centreline migration is an appropriate solution for the flow field and the bed topography of meandering rivers. Over the years, multiple approaches have been developed to describe the flow field and bed topography in systems forced by the axis curvature. Other researchers have proposed different linear analytical solutions (Blondeaux & Seminara, 1985; Crosato, 1990; Ikeda et al., 1981; Johannesson & Parker, 1989; Motta et al., 2012; Zolezzi & Seminara, 2001),

because of their ease of use and relative speed in the calculations. Some researchers have added non-linearity to the mix (Blanckaert & de Vriend, 2010; Bolla Pittaluga et al., 2009; Eke, Czapiga, et al., 2014; Seminara & Tubino, 1992) or considered the effects of varying width (Frascati & Lanzoni, 2013; Luchi et al., 2011). However, these additions increase the complexity, and they were often only applied to the periodic case. Conversely, the linear solution is simpler, yet still representative of the main features of the overall phenomenon. Among the linear solutions, the one developed by Zolezzi and Seminara (2001) (ZS) stands out for a variety of reasons. In particular, this solution was developed to encompass the upstream morphodynamic influence for an arbitrary distribution of curvature. Describing the upstream morphodynamic influence is essential for understanding the effects of the axis curvature on the upstream points, which is key when trying to explain phenomena such as the upstream migration of bends or the overdeepening shown by Struiksma et al. (1985). The arbitrary distribution of curvature also enables the description of the convoluted and complex shapes displayed by real meandering rivers. Other researchers often used a periodic solution (Blondeaux & Seminara, 1985; Seminara & Tubino, 1989), which is useful for understanding the underlying processes, but it is less realistic than the ZS solution. Camporeale et al. (2007) compared a series of these linear models (Ikeda et al., 1981; Johannesson & Parker, 1989; Zolezzi & Seminara, 2001) and concluded that all of these approaches are valid, provided they are used appropriately. However, they showed how the model derived from the ZS flow field solution best represented the evolution of the Tanaro River (Figure 13).

2.1.4.1 Formulation of the two-dimensional model for meandering rivers

A brief discussion of the solution proposed by Zolezzi and Seminara (2001) is provided here, but a more in-depth analysis can be found in the original article.

To describe the velocity at the bank needed for Equation 7 a two-dimensional model would suffice, however, this would not be able to represent the curvature-induced secondary

circulations described by Rozovskii (1957), which are only visible in a three-dimensional formulation. Therefore, a three-dimensional model is required, consisting of the Reynolds equations for the fluid phase and an appropriate formulation of the Exner equation for the evolution of the bed topography. By extending the flow decomposition proposed by Kalkwijk and De Vriend (1980), it is possible to encompass the effects of the three-dimensional circulation when averaging over the vertical coordinate to obtain a two-dimensional formulation. Furthermore, under the hypothesis that the timescale of the evolution of the bed morphology is longer than the time evolution of the flow field, the time derivative of the flow terms can be neglected.

The resulting equations are a modified version of the shallow water equations coupled with a two-dimensional form of the Exner equation:

$$U \frac{\partial U}{\partial s} + V \frac{\partial U}{\partial n} + \frac{\partial H}{\partial s} + \beta \frac{\tau_s}{D} = \nu_0 f_{11} + O(\nu_0), \quad (14)$$

$$U \frac{\partial V}{\partial n} + V \frac{\partial V}{\partial n} + \frac{\partial H}{\partial n} + \beta \frac{\tau_n}{D} = \nu_0 g_{11} + O(\nu_0), \quad (15)$$

$$\frac{\partial DU}{\partial s} + \frac{\partial DV}{\partial n} = \nu_0 m_{11}, \quad (16)$$

$$\frac{\partial F_{r0}^2 H - D}{\partial t} + \mathcal{Q}_{s0} \left(\frac{\partial q_s}{\partial s} + \frac{\partial q_n}{\partial n} \right) = \nu_0 n_{11}, \quad (17)$$

with boundary conditions

$$V|_{n=\pm 1} = q_n|_{n=\pm 1} = 0. \quad (18)$$

Figure 4 shows the notation used in Equations (14-18) for the cross-section. In particular, the shape of a cross-section is described with its depth (D), free surface elevation (H) and river bed elevation (η), all of which are scaled using the uniform flow depth (D_0^*). The coordinates s and n are scaled with the already presented B^* , which is considered constant. Since it is a two-dimensional model, the flow field is described with the longitudinal velocity (U) and the transverse velocity (V), scaled both with the uniform flow longitudinal velocity (U_0^*). Other relevant flow parameters include the discharge (Q) and the Froude

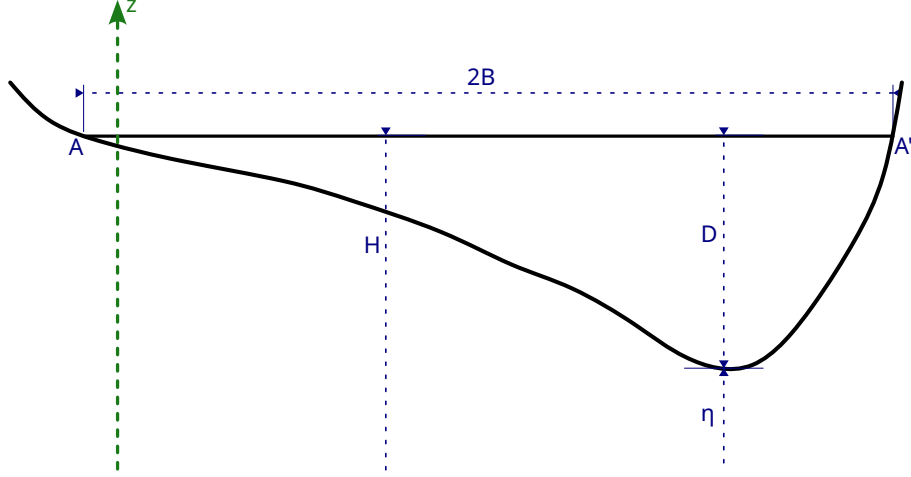


Figure 4 – Example of the notation of a cross-section (XS) for a meandering river.

number (F_r).

An important step in modelling morphodynamic processes is defining the closures that determine the shear stress (τ) and sediment discharge (Q_s). In particular τ can be projected onto the s and n axes as follows:

$$\tau_s = C_f (d_s, R_p, \tau_*) U |U|, \quad (19)$$

$$\tau_n = C_f (d_s, R_p, \tau_*) V |V| + \tau_H, \quad (20)$$

with friction coefficient (C_f), which will be described more thoroughly in section 2.1.4.2, and the correction for the secondary circulations (τ_H), which is derived from the flow decomposition proposed by ZS. The Q_s is defined as

$$Q_s^* = 2B^* \sqrt{g \Delta d_g^3} \Phi(\tau_*, R_p), \quad (21)$$

with the key element of this formula being the sediment transport function (Φ), which will be discussed in section 2.1.4.2. Equation 17 uses the components of Q_s which are the results of the deviation caused by gravity (Talmon et al., 1995).

The coefficients f_{11} , g_{11} , m_{11} and n_{11} depend on the correction for the secondary circulation

and on the conversion between the Cartesian and the curvilinear reference system and they can be found in ZS. The time (t) is scaled with $\frac{B^*}{U_0^*}$. Lastly, a few other parameters arise from the scaling of the equations and from the closure relationships. These parameters are generally used, because it is possible to use them to completely define the bankfull geometry of a river. Moreover, being non-dimensional means they can also be used to compare rivers across different scales. The parameters are:

- the relative submerged density of sediments (Δ):

$$\Delta = \frac{\rho_s - \rho}{\rho}; \quad (22)$$

- the aspect ratio (β):

$$\beta = \frac{B^*}{D^*}; \quad (23)$$

- the Shields parameter (τ_*), which for the uniform flow definition reads:

$$\tau_* = \frac{D^* S^*}{\Delta d_g}; \quad (24)$$

- the relative roughness (d_s):

$$d_s = \frac{d_g}{D^*}; \quad (25)$$

- the Reynolds' particle number (R_p):

$$R_p = \frac{\sqrt{\Delta g d_g^3}}{\nu}; \quad (26)$$

with the water density (ρ) and the water kinematic viscosity (ν).

2.1.4.2 Closures

As noted in the previous section and in general when talking about river hydro- and morphodynamics, the need to use specific closure relationships for the flow resistance and for the sediment transport capacity arises, to evaluate C_f and Φ . There are several formulas and several parameters used for this scope and they can be divided by the means in which they were derived. Some formulas are obtained from purely theoretical findings, while others are based on laboratory or river data that describe the processes at play. Finally, there are regime formulas which generally use a more holistic approach, fitting the data to find a relationship that describe the river behaviour as a whole across multiple scales.

Generally, rivers are divided into two main categories, based on the prevalent grain size of the sediments considered:

- gravel bed rivers, with a median sediment grain size (d_{g50}) greater than 2 mm;
- sand bed rivers, with a d_{g50} smaller than 2 mm.

This categorization is relevant for the evaluation of the transport capacity or the flow resistances, because it changes the mechanism behind the resistance and transport process. For that reason the two classes are usually treated differently.

Gravel bed rivers Gravel bed rivers are generally easier to describe, at least for the mild sloped rivers, which are the rivers generally showing meandering behaviour. Among the various possible choices, the resistance formulas used throughout this PhD thesis were the classic logarithmic formula by Keulegan (1938), which was derived from the theoretical findings for the flow resistance in a pipe, and the regime formula by Parker et al. (2007), derived from a large database of gravel bed rivers. The Keulegan (1938) formula reads

$$\frac{1}{\sqrt{C_f}} = 6 + 2.5 \ln \left(\frac{1}{2.5d_s} \right), \quad (27)$$

but can also be fitted with a power law

$$\frac{1}{\sqrt{C_f}} = A ds^B, \quad (28)$$

which in the case of the Keulegan (1938) has an exponent of around $B \sim 0.17 - 0.18$. The regime formula by Parker et al. (2007) is also a power law, with exponent $B = 0.263$ and coefficient $A = 3.71$.

For the sediment transport the formulas implemented in this dissertation were the classic Meyer-Peter and Müller (1948) formula, the Parker (1978) formula and the Parker (1990) formula. The first one is based on laboratory data and it is often used, being one of the oldest ones, but the other two are considered more accurate and are both based on field data. However, while being quite close to each other, the Parker (1990) does not present an explicit threshold for incipient motion, which allows for an easier manipulation in a modelling setting and so it was generally preferred in this PhD study.

Sand bed rivers For sand bed rivers the picture is a little more complex due to the bigger relevance of the suspended sediment, that will however not be treated in this dissertation, and the presence of dunes, that are rather relevant for the evaluation of the flow resistance, as it will be discussed here.

The sediment transport formula used was the one developed by Engelund and Hansen (1967) for the total transport, to avoid the need for two separate formulas for the suspended and bed loads, which, while being more accurate, introduces unneeded complexity.

For the resistance formulas two possibilities were investigated, the regime formula by Wilkerson and Parker (2011) and the logarithmic formula by Keulegan (1938) adapted by Engelund and Hansen (1967) for the presence of dunes. The first formula is just a power law just like in Equation 28, with exponent $B = 0.413$ and coefficient $A = 1.44 R_p^{0.197}$. Since it is a regime formula it mixes data from a series of sand bed rivers, but it does not distinguish between the presence of absence of dunes, which can change dramatically the resistance.

For that reason that was quickly abandoned in this PhD project in favour of Engelund and Hansen (1967) adaptation of the Keulegan (1938) formula. However, there are different dune correction formulas that can be used.

A commonly used approach to evaluate the effects of the dunes on the flow resistance was first proposed by Einstein (1950), who proposed to divide the total C_f into a term caused by the skin friction C'_f , which always exists and is due to the sediment related roughness, and a term caused by the form drag C''_f , only present if bedforms exists. This two-components behaviour is also true for the τ_* , that can be divided in a component caused by the skin friction τ'_* and one caused by the form drag τ''_* . Einstein (1950) proposed to evaluate the skin friction roughness C'_f using a formula like the Keulegan (1938) one using the boundary layer thickness (D') instead of the depth (D) finding

$$\frac{1}{\sqrt{C'_f}} = 6 + 2.5 \ln \left(\frac{D'}{2.5d_g} \right). \quad (29)$$

Under the hypothesis that there is no meaningful exchange of energy between the upper and boundary layer flow, Engelund and Hansen (1967) find that

$$\frac{C'_f}{C_f} = \frac{D'}{D} \quad (30)$$

and with the similarity principle they find

$$\frac{C'_f}{C_f} = \frac{\tau'_*}{\tau_*}. \quad (31)$$

With this two results the resistance formula can be rewritten for C_f as

$$\frac{1}{\sqrt{C_f}} = \sqrt{\frac{\tau'_*}{\tau_*}} \left(6 + 2.5 \ln \left(\frac{1}{2.5d_s} \frac{\tau'_*}{\tau_*} \right) \right) \quad (32)$$

which is the formula proposed by Engelund and Hansen (1967). They then proposed a

formula for the skin friction contribution for the Shields parameter (τ'_*) based on flume experiments on dunes that reads

$$\tau'_* = 0.06 + 0.4\tau_*^2. \quad (33)$$

Using some additional laboratory data Engelund and Fredsøe (1982) later updated the formulation to

$$\tau'_* = 0.06 + 0.3\tau_*^{\frac{3}{2}}. \quad (34)$$

The Engelund and Hansen (1967) is one of the most used approaches and it was used for the most part of this PhD work. However, the newly published book by Seminara et al. (2023b) pointed towards the equation proposed by Wright and Parker (2004). Using data collected from six meandering rivers at different discharges, they show how Engelund and Hansen (1967) tends to overestimate the skin friction for higher values of τ_* , albeit working quite well for lower values of τ_* . Engelund and Fredsøe (1982) seems a little more accurate, but it is still off compared to the river data. Consequently, they propose a new formulation obtained fitting this river data that can be written as

$$\tau'_* = 0.05 + 0.7 \left(\tau_* F_r^{0.7} \right)^{0.8}. \quad (35)$$

The structure seems rather similar to Engelund and Hansen (1967) and Engelund and Fredsøe (1982), however there is a notable difference which is the presence of the Froude number (F_r). The unfortunate effect of the presence of F_r adds the need to iterate, since it depends on the velocity and so on the resistance itself, and this adds complexity both to for the evaluation of C_f and in particular for its derivative terms C_{fD} and C_{fT} . For this reason, during this PhD study, a new interpolation of the same data was attempted, substituting F_r with some other parameter, as for example d_s , but this did not lead to a formula as accurate as the one in Equation 35. Ultimately, the formula proposed by Wright and Parker (2004)

was used in its original form, iterating when necessary.

2.1.4.3 Linearization of the two-dimensional model

To solve Equations (14-18) it is convenient to impose that the flow and topography perturbations are small enough, which is generally true if when looking at perturbations that scale with ν_0 . When doing so the problem can be linearized to allow for an easier analytical solution.

ZS state that this perturbation is superimposed on a uniform flow configuration and they obtain that

$$(U, V, D, H) = (1, 0, 1, h_0) + \nu_0(u, v, d, h) + O(\nu_0^2). \quad (36)$$

Substituting Equation 36 in Equations (14-18) and imposing that the bed morphology is in equilibrium with the flow field, which allows neglecting the time derivative in Equation 17, they find

$$\left(\frac{\partial}{\partial s} + a_1 \right) u + \frac{\partial h}{\partial s} + a_2 d = nb_1 \mathcal{C}(s), \quad (37)$$

$$\left(\frac{\partial}{\partial s} + a_3 \right) v + \frac{\partial h}{\partial n} = b_2 \mathcal{C}(s) + b_3 \mathcal{C}'(s) + b_5 \mathcal{C}''(s), \quad (38)$$

$$\frac{\partial u}{\partial s} + \frac{\partial v}{\partial n} + \frac{\partial d}{\partial s} = 0, \quad (39)$$

$$a_4 \frac{\partial u}{\partial s} + \frac{\partial v}{\partial n} + \left(a_5 \frac{\partial}{\partial s} + a_6 \frac{\partial^2}{\partial n^2} \right) d - F_{r0}^2 a_6 \frac{\partial^2 h}{\partial n^2} = 0. \quad (40)$$

with boundary conditions

$$v = 0 \quad (n = \pm 1) \quad (41)$$

$$\frac{\partial(F_{r0}^2 h - d)}{\partial n} = b_4 \mathcal{C}(s) + b_6 \mathcal{C}'(s) \quad (n = \pm 1) \quad (42)$$

were a_{1-6} and b_{1-6} are coefficients that can be found in the original article and they are a combination of the base uniform flow, the parametrization of the secondary circulations

and the C_{fD} , the C_{fT} , the Φ_D and the Φ_T , derivatives in D and τ_* of the friction coefficient (C_f) and sediment transport function (Φ), written as

$$C_{fD} = \frac{1}{C_{f0}} \left. \frac{\partial C_f}{\partial D} \right|_0, \quad (43) \quad \Phi_D = \frac{1}{\Phi_0} \left. \frac{\partial \Phi}{\partial D} \right|_0, \quad (45)$$

$$C_{fT} = \frac{\tau_{*0}}{C_{f0}} \left. \frac{\partial C_f}{\partial \tau_*} \right|_0, \quad (44) \quad \Phi_T = \frac{\tau_{*0}}{\Phi_0} \left. \frac{\partial \Phi}{\partial \tau_*} \right|_0. \quad (46)$$

The linearized system can then be solved in two different ways:

- under the hypothesis of a periodic train of meanders, as proposed by Blondeaux and Seminara (1985), Seminara and Tubino (1989) and Seminara and Tubino (1992), with a simpler solution that works however only on regular meanders;
- using the expansion in Fourier series, which has the advantage of being applicable to meanders with an arbitrary distribution of curvature, as proposed by ZS.

The latter approach is the one followed in this manuscript up until now and ultimately is a more adaptable approach to a variety of use cases. However, the ease of use of the periodic solution allows for faster testing of simplified models, before introducing more complexity to the mix. For these reason both approaches will be briefly introduced. It is worth nothing that the Fourier approach can be simplified for the use on a periodic planform (Seminara et al., 2001), but the solution proposed in the next paragraph remains more elegant and easier to use.

2.1.4.4 Periodic solution

A periodic train of meanders is originated by simply using Equation 4 and it is shown in Figure 5. It is not representing a real river, however it is able to describe the underlying processes caused by the curvature forcing.

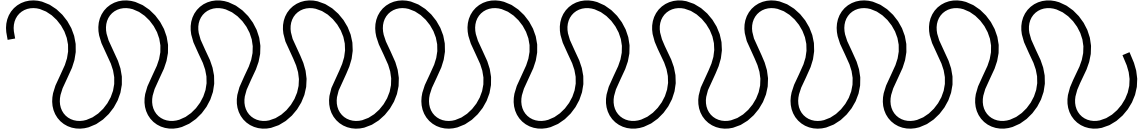


Figure 5 – Example of a periodic train of meander bends.

The system of Equations (37-40) is not exactly the one solved by Blondeaux and Seminara (1985) or Seminara and Tubino (1989), because some of the constants are defined in slight different fashion, but the structure is the same. The system needs to be transformed from a system of partial differential equations to a system of ordinary differential equations, to ease the manipulation and the solution of the equations. To do so Blondeaux and Seminara (1985) employ a variable separation imposing that the perturbation can be described with a part accounting for the variability in n and a complex exponential describing the variability in s . The variable separation can be written as

$$(u, v, d, h) = (U_{1m}(n), V_{1m}(n), D_{1m}(n), H_{1m}(n))e_1 + c.c. \quad (47)$$

with the complex conjugate ($c.c.$) and the complex exponential (e_1), which can be generalized as

$$e_m = e^{i\lambda_m s}. \quad (48)$$

The meander wavenumber for the m -harmonic (λ_m) can be written as the meander wavenumber (λ) multiplied for the harmonic number (m):

$$\lambda_m = m\lambda. \quad (49)$$

The system can be rewritten as a function of only n as

$$a_1 U_{1m} + a_2 H_{1m} + a_3 D_{1m} = b_1(n), \quad (50)$$

$$a_4 V_{1m} + a_5 \frac{dH_{1m}}{dn} = b_2(n), \quad (51)$$

$$a_6 U_{1m} + \frac{dV_{1m}}{dn} + a_6 D_{1m} = b_3(n), \quad (52)$$

$$a_9 U_{1m} + a_7 \frac{dV_{1m}}{dn} + a_8 \frac{d^2(D_{1m} - F_{r0}^2 H_{1m})}{dn^2} + a_{10} D_{1m} + a_{11}(F_{r0}^2 H_{1m} - D_{1m}) = b_4(n), \quad (53)$$

with boundary conditions

$$V_{1m} = 0 \quad n = \pm 1, \quad (54)$$

$$\frac{d(F_{r0}^2 H_{1m} - D_{1m})}{dn} = b_5 \quad n = \pm 1, \quad (55)$$

and where the coefficients a_{1-11} and b_{1-5} can be retrieved from Appendix A and they are slightly different from the ones of ZS of Equations (37-40), as said earlier.

Manipulating Equations (50-55) it is possible to obtain a fourth-order ordinary differential equation for the transverse velocity that reads

$$\frac{d^4 V_{1m}}{dn^4} + \Gamma_1 \frac{d^2 V_{1m}}{dn^2} + \Gamma_2 V_{1m} = \Gamma_0, \quad (56)$$

$$V_{1m} = 0 \quad \frac{d^2 V_{1m}}{dn^2} = \Gamma_3 \quad n = \pm 1. \quad (57)$$

Equations (56-57) can be solved first for the homogeneous part and with a particular solution for the non-homogeneous problem, finding

$$V_{1m} = V_0 + V_1 \cosh(\lambda_1 n) + V_2 \cosh(\lambda_2 n), \quad (58)$$

After solving for V_{1m} , the solution for (U_{1m}, D_{1m}, H_{1m}) is trivial and can be written as

$$H_{1m} = H_0 n + H_1 \sinh(\lambda_1 n) + H_2 \sinh(\lambda_2 n), \quad (59)$$

$$D_{1m} = D_0 n + D_1 \sinh(\lambda_1 n) + D_2 \sinh(\lambda_2 n), \quad (60)$$

$$U_{1m} = U_0 n + U_1 \sinh(\lambda_1 n) + U_2 \sinh(\lambda_2 n), \quad (61)$$

with all the coefficients for Equations (58-61) that are reported in Appendix A.

The periodic solution derived by Blondeaux and Seminara (1985) first showed the existence of a singularity in the response of flow field to a particular combination of β and λ , which they identified as the resonant condition of the linear solution. The resonant condition will be described in depth in section 2.1.4.6.

Exact solution for the evolution of a periodic train of meanders On top of being easier to manipulate and to use for testing purposes, the periodic solution for the flow field allows also for an explicit solution of Equation 13.

For a periodic solution the expression for the angle θ is easily described as

$$\theta = \sum_m (\theta_m(t) e_m + c.c.) \quad m = 1, 3, \dots \quad (62)$$

and the expression for ζ is readily obtained using the decomposition proposed earlier for the transverse velocity and Equation 7, finding

$$\zeta = E \sum_m (-2im\lambda\theta_m U_{1m} e_m), \quad (63)$$

where the term $-im\lambda\theta_m$ derives from the presence of ν_0 in the decomposition. Since the curvature can be defined as mentioned in Equation 1, the resulting term is the one highlighted above.

As described in section 2.1.3.1, to retain the non-linearity of Equation 13 is worth at least

using the first and third harmonic (all the even harmonic would disappear due to the antisymmetric nature of the problem (Seminara et al., 2001)). With some algebra one can rearrange Equation 13 and separate the terms that are multiplied for e_0 , e_1 and e_3 , finding the following system.

$$\frac{d\theta_1}{dt} = i\lambda E \left(\theta_1(A_0 + c.c) - \bar{\theta}_1 A_2 + 3\theta_3 \bar{A}_2 - 3\bar{\theta}_3 A_4 \right) + i\lambda E(-2i\lambda\theta_1 U_{11}) \quad (64)$$

$$\frac{d\theta_3}{dt} = i\lambda E \left(\theta_1 A_2 - \bar{\theta}_1 A_4 + 3\theta_3(A_0 + c.c) - 3\bar{\theta}_3 A_6 \right) + i3\lambda E(-6i\lambda\theta_3 U_{13}) \quad (65)$$

$$\frac{d\lambda}{dt} = i\lambda^2 E(A - \bar{A}) \quad (66)$$

with the coefficients A , A_0 , A_2 , A_4 and A_6 that are reported in Appendix A and the $\bar{}$ superscript indicates the complex conjugate of the variable. These three equations can be easily solved analytically or with a numerical method such as a Fourth Order Runge-Kutta, leading to the distribution of the angle θ of every planimetry point with Equation 62 that can be used to reconstruct the planform of the river.

While this solution is quite helpful for simplified models, it presents some limitations. In particular the periodic solution there is not able to represent the evolution of a river after a cutoff happens, since it would not be possible to describe the variability of the flow field in the s coordinate with complex exponential proposed in Equation 47.

2.1.4.5 Solution for an arbitrary distribution of curvature

For the formulation of the arbitrary curvature distributions solution proposed by ZS, it is also necessary to employ a separation of variables to reduce the system in Equations (37-42) from partial differential equations to ordinary differential equation. In this case however, it is more beneficial to impose the variability in n and solve the remaining equation in s , reversing the approach of the periodic solution.

Firstly, ZS use a decomposition to remove the non-homogeneous component from the

boundary conditions in Equation 42 that reads

$$(u, v, h, d) = (0, 0, (\bar{h}_1 \mathcal{C} + \bar{h}_2 \mathcal{C}' + \bar{h}_3 \mathcal{C}''), (\bar{d}_1 \mathcal{C} + \bar{d}_2 \mathcal{C}' + \bar{d}_3 \mathcal{C}''))n + (\hat{u}, \hat{v}, \hat{h}, \hat{d}). \quad (67)$$

Then, they remove the partial character of the system imposing that the variability in n is describable with a Fourier series as

$$(\hat{u}, \hat{h}, \hat{d}) = \sum_{m=0}^{\infty} (u_m(s), h_m(s), d_m(s)) \sin(Mn) \quad (68)$$

for the antisymmetric variables and

$$\hat{v} = \sum_{m=0}^{\infty} v_m(s) \cos(Mn) \quad (69)$$

for the transverse velocity, which is the only symmetric variable.

With this variable separation, ZS find m systems depending only on s , one for each Fourier mode m that can be written as

$$\left(\sigma_4 \frac{d^4}{ds^4} + \sigma_3 \frac{d^3}{ds^3} + \sigma_2 \frac{d^2}{ds^2} + \sigma_1 \frac{d}{ds} + \sigma_0 \right) u_m(s) = -A_m \sum_{j=0}^6 \rho_{j+1} \frac{d^{(j)} \mathcal{C}}{ds^{(j)}} \quad (70)$$

$$(d_m(s), v_m(s), h_m(s)) = \sum_{j=1}^4 (d_{mj}, v_{mj}, h_{mj}) \frac{d^{(j-1)} u_m}{ds^{(j-1)}} + A_m \sum_{j=5}^9 (d_{mj}, v_{mj}, h_{mj}) \frac{d^{(j-1)} \mathcal{C}}{ds^{(j-1)}} \quad (71)$$

with the various coefficients reported in their article and its appendix. These systems can be solved with the method of variation of constants finding

$$(u_m, v_m, d_m, h_m) = \sum_{j=1}^4 \left((1, m_j, \delta_{mj}, \xi_{mj}) \left(\hat{A}_m g_{j0} \int_{s_0}^s e^{\lambda_{mj}(s-t)} \mathcal{C}(t) dt + c_{mj} e^{\lambda_{mj}(s-s_0)} \right) + \hat{A}_m \sum_{k=1}^9 \Gamma_{jk}^{(u,v,d,h)} \frac{\partial^{(k-1)} \mathcal{C}}{\partial s^{(k-1)}} \right). \quad (72)$$

Among the reported parameter, the most interesting ones are c_{mj} , the coefficients to be

determined with the boundary conditions, and the λ_{mj} , the characteristics exponents for the solution.

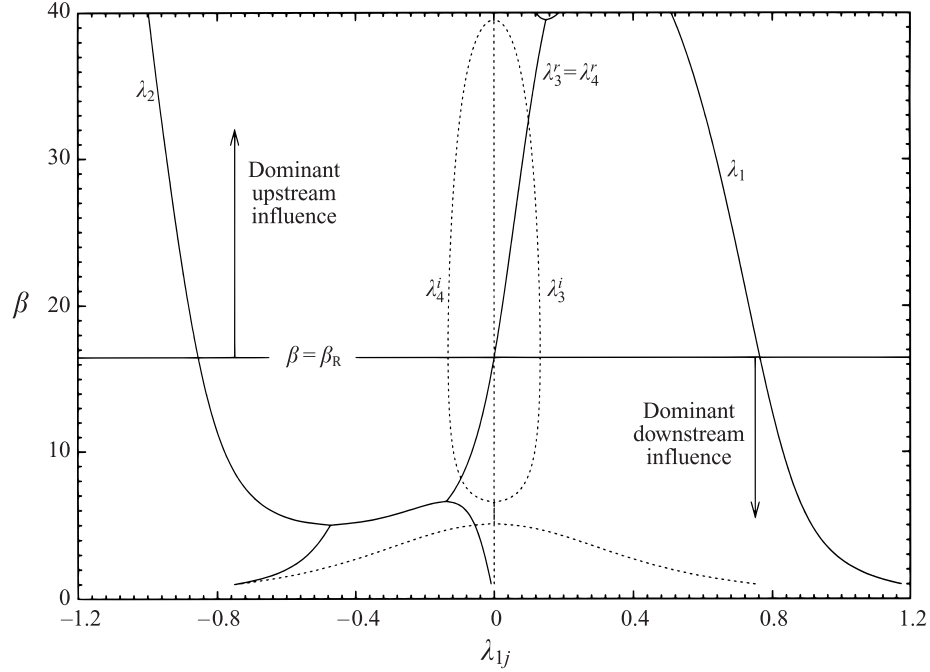


Figure 6 – Characteristic exponents for the first Fourier mode of the solution in Equation 72 for $\tau_* = 0.1$ and $d_s = 0.01$. The solid lines correspond to the real part of the exponents, while the dotted lines correspond to the imaginary part. The graph is taken from Zolezzi and Seminara (2001)

Of these four exponents, two are real, one negative and one positive, while the other two are complex conjugates. As shown in Figure 6, the real part in the two complex ones is negative when the β is lower than the resonant aspect ratio (β_R), defined as the threshold found by Blondeaux and Seminara (1985), for the first Fourier mode or m -times β_R , for higher modes, where the characteristic exponents for the solution of Equation 72 (λ_{mj}) are easily calculated as

$$\lambda_{mj} = m\lambda_{1j}. \quad (73)$$

Each term of the solution in Equation 72 will have an upstream or downstream influence defined by the sign of the exponent, with negative exponents corresponding to term with a downstream influence and vice versa. As shown in Figure 6, when β is lower than β_R

(sub-resonant regime), three of the four exponents have a negative real part, leading to a dominant downstream influence, while for the super-resonant regime the sign of the exponents reverses and the dominant influence is upstream. Here is reported the solution in the sub-resonant regime for a point of coordinate s as an example to see how the various terms behave, under the hypothesis that λ_{m1} is the positive one (Zolezzi & Seminara, 2001).

$$\begin{aligned}
(u_m, v_m, d_m, h_m) = & \underbrace{-\hat{A}_m g_{10}(1, m_1, \delta_{m1}, \xi_{m1}) \int_s^{s_0+L} e^{-\lambda_{m1}(t-s)} \mathcal{C}(t) dt}_{1 - \text{upstream propagating influence}} \\
& + \underbrace{\hat{A}_m \sum_{j=2}^4 g_{j0}(1, m_j, \delta_{mj}, \xi_{mj}) \int_{s_0}^s e^{\lambda_{mj}(s-t)} \mathcal{C}(t) dt}_{2 - \text{downstream propagating influence}} \\
& + \underbrace{\hat{A}_m \sum_{j=1}^4 \left(\sum_{k=1}^9 \left(\Gamma_{jk}^{(u)}, \Gamma_{jk}^{(v)}, \Gamma_{jk}^{(d)}, \Gamma_{jk}^{(h)} \right) \frac{\partial^{(k-1)} \mathcal{C}}{\partial s^{(k-1)}} \right)}_{3 - \text{local effect}} \\
& + \underbrace{c_{m1}(1, m_1, \delta_{m1}, \xi_{m1}) e^{-\lambda_{mj}(s_0+L-s)}}_{4 - \text{upstream effect of downstream boundary condition}} \\
& + \underbrace{\sum_{j=2}^4 c_{mj}(1, m_j, \delta_{mj}, \xi_{mj}) e^{\lambda_{mj}(s-s_0)}}_{5 - \text{downstream effect of upstream boundary condition}}
\end{aligned} \tag{74}$$

There are five different terms that can be identified in Equation 74 described here:

1. one contribution for the upstream morphodynamic influence of the section located downstream the chosen point s ;
2. three contributions for the downstream morphodynamic influence of the stretch located upstream chosen point s ;
3. four contributions for the local effect of the curvature around the chosen point s ;
4. one contribution for the upstream morphodynamic influence of the downstream end boundary condition:

5. three contributions for the downstream morphodynamic influence of the upstream end boundary condition.

Even though in the sub-resonant regime there is a prevalent downstream morphodynamic influence, the first and fourth term display a component of upstream influence. ZS showed that the contributions that pertain to the real exponents (in the case of Figure 6 λ_1 and λ_2) are quickly damped (in a few channel widths), while the contributions that pertain to the complex exponents are oscillatory and weakly damped, and so the downstream morphodynamic influence prevails. The picture reverses for the super-resonant when the real part of the complex exponents changes sign and so the upstream morphodynamic influence prevails.

It is also important to note that Lanzoni and Seminara (2006) showed that the third term could be simplified considering only $k = 1$, so keeping only the term containing the curvature itself, while all the other terms are vanishing and so can be neglected, at least for the evaluation of the flow field.

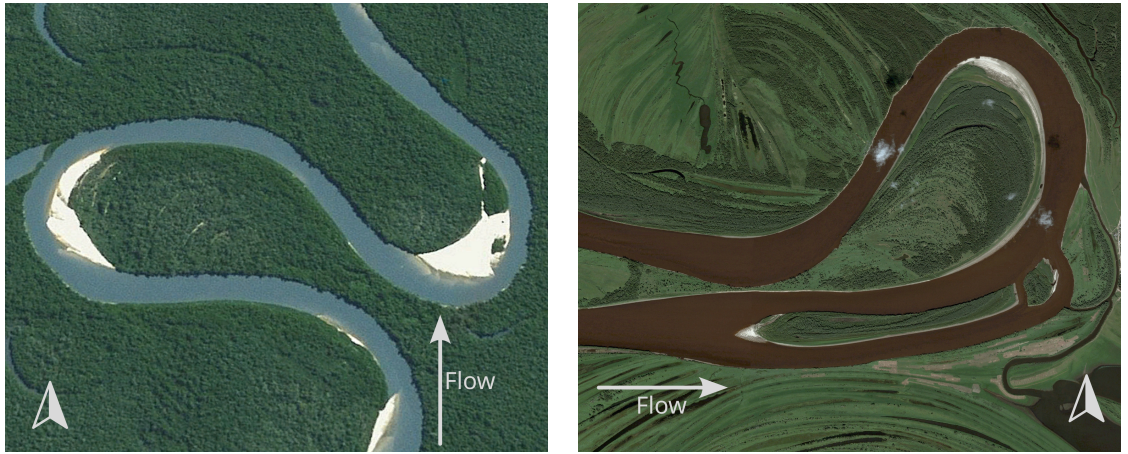
2.1.4.6 Resonance

As mentioned above it is possible to define two different regimes that depend on the aspect ratio (β) and its position compared to the resonant aspect ratio (β_R) found by Blondeaux and Seminara (1985).

This resonant condition is important because it generates a singularity in the linear solution as showed by Blondeaux and Seminara (1985) and Seminara and Tubino (1992), provided that both the meander wavenumber (λ) and the aspect ratio (β) of the meander are equal to their resonant value. This leads to an amplification of the erosion rate, while at the same time it inhibits the upstream or downstream migration of the bends (Seminara, 2006), ultimately leading an infinite flow field solution. Knowing this, it is easy to see that the resonant condition corresponds to fast-growing bends, that only elongates without moving upstream or downstream, but, while this is theoretically possible, there are slim chance of

that happening in a natural setting because of the double constraint on the wavenumber and aspect ratio. It is more interesting to describe what happens in the sub- and super-resonant regimes.

As detailed by Seminara et al. (2001), sub-resonant bends migrates downstream and are skewed upstream, as the ones in Figure 7a, while super-resonant ones exhibit the opposite behaviour, as the ones in Figure 7b. One can clearly infer that the position of the maximum erosion rate moves from downstream the bend apex to upstream the bend apex when the aspect ratio of a bend increases, as shown by Monegaglia et al. (2019), explaining the different behaviour with the regime of the river. It is also interesting to note that the behaviour of a bend is not set in stone, but can change during the evolution of a river. In particular, the bend regime has been shown by Zolezzi, Luchi, and Tubino (2009) to change from the super- to sub-resonant when the bends elongate and become more sinuous.



(a) *Upstream skewed bend - Rio Culene (Brazil)*
Google Earth Image ©2024 CNES / Airbus

(b) *Downstream skewed bend - Irtyš River (Russia)*
Google Earth Image ©2024 Maxar Technologies

Figure 7 – Examples of upstream (a) and downstream (b) skewed bends in meandering rivers.

It is important to note that the β_R is a function of the τ_* , the d_s and potentially also the R_p , depending on the resistance and transport formula used. The regime of a river or a bend can only be determined knowing all the parameter of the bankfull geometry, which is often a complex task. However, using the skewing angle as a proxy, one could actually determine the regime of the bend just by measuring this angle, which much easier, particularly when

using satellite data. As an example of that, Guo et al. (2019) analysed the skewing angle in a series of meandering rivers from satellite data, obtaining a result that is analogous with what Zolezzi, Luchi, and Tubino (2009) showed. In particular, they observed the tendency of less sinuous, so generally younger bends, to be skewed downstream, which would indicate a super-resonant regime, while more sinuous bends, so older ones, showed more upstream skewing, possibly indicating a sub-resonant regime. Guo et al. (2019) did not attempt a direct comparison with the actual regime, since without the complete bankfull geometry this is rather difficult to infer, but their observations fit quite well with those of Zolezzi, Luchi, and Tubino (2009).

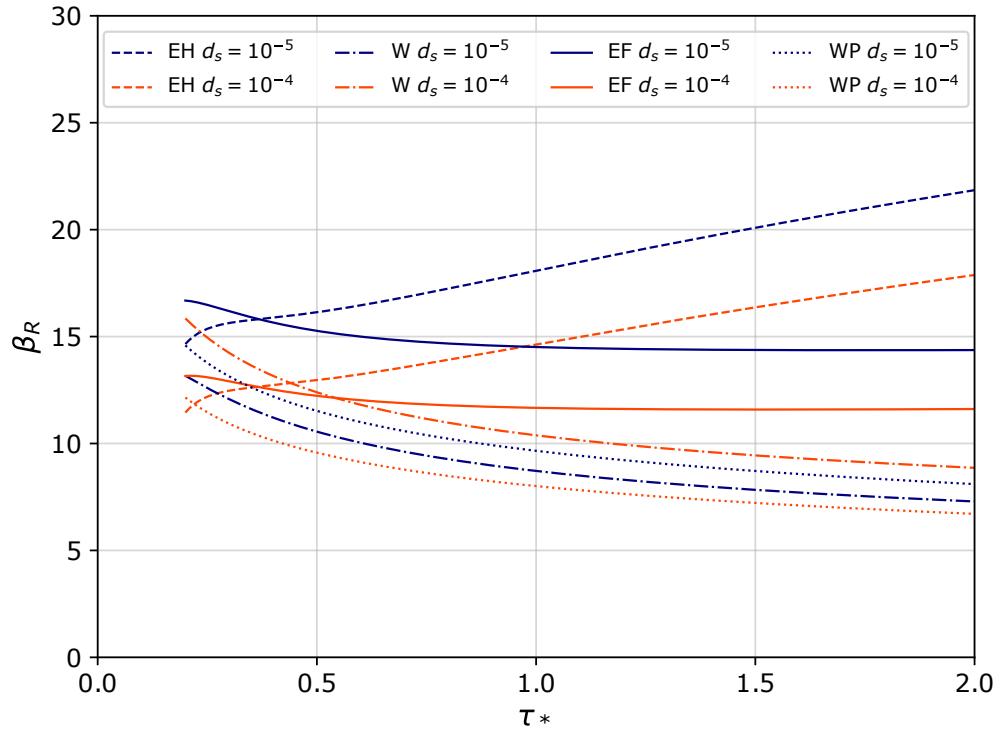


Figure 8 – β_R evaluated for sand bed rivers with different resistance formulas with the code developed by Redolfi (2023) when varying the Shields parameter (τ_*) between 0.2 and 2. For each case two different values of relative roughness (d_s) were used, $1 \cdot 10^{-5}$ in the blue lines and $1 \cdot 10^{-4}$ in the orange lines. The transport formula used is always the one proposed by Engelund and Hansen (1967), while for the resistance formulas are reported the results for the Engelund and Hansen (1967) (EH) dunes correction of the Keulegan (1938) formula in the dashed lines, for the Engelund and Fredsøe (1982) (EF) dunes correction in the continuous lines, for the Wright and Parker (2004) (W) dunes correction in the dashed dotted lines and for the Wilkerson and Parker (2011) (WP) regime formula in the dotted lines.

Since the resonant condition depends on the bankfull geometry of the river, the closures chosen for its evaluation can be quite relevant, in particular when looking at the different sand bed river resistance formulas described in section 2.1.4.2. In Figure 8 are reported the graphs obtained with the code by Redolfi (2023) for β_R using the Engelund and Hansen (1967) transport formula and the different resistance formulas proposed for sand bed rivers. As it appears quite clearly in the graph that, while the values are not that far off for low τ_* , this is not true for higher values of τ_* . Looking more into the behaviour of every formula, the Engelund and Hansen (1967) one is the only one that present an increasing β_R when τ_* increases, while for the others β_R is always decreasing. Moreover, the formula proposed by Wright and Parker (2004) is the only one with higher β_R for lower d_s . It becomes apparent then how important is the choice of the closures and how big of an impact this choice has on the simulations. In chapter 3 will be reported some comparisons between simulations with different closures.

2.1.5 *Bankfull geometry parameter update*

Once the erosion law and the flow field solution are set, the only thing missing is a way to describe the evolution of the bankfull geometry parameters. As shown in section 2.1.4, the proposed flow field is a superimposed perturbation of a uniform flow field, that can be considered the bankfull geometry of the modelled river. This could be kept constant along the entire simulation, but that is not necessarily accurate. Generally, in the development of these models, it is imposed that the floodplain slope has to remain constant, and so when a modelled river elongates, its slope has to decrease in order to follow this constraint, and vice versa when a cutoff happens and the river shortens. It is trivial then to derive how the bankfull geometry varies, when keeping the width constant, knowing that a decreasing slope entails an increase in depth, which influences also the friction coefficient, and a decrease in velocity. Here the relations used by Bogoni et al. (2017) are reported as an

example:

$$\beta^{k+1} = \left(\frac{C_f^k}{C_f^{k+1}} \right)^{+\frac{1}{3}} \left(\frac{\sigma^k}{\sigma^{k+1}} \right)^{+\frac{1}{3}} \beta^k, \quad (75)$$

$$\theta^{k+1} = \left(\frac{C_f^k}{C_f^{k+1}} \right)^{-\frac{1}{3}} \left(\frac{\sigma^k}{\sigma^{k+1}} \right)^{+\frac{2}{3}} \theta^k, \quad (76)$$

$$d_s^{k+1} = \left(\frac{C_f^k}{C_f^{k+1}} \right)^{+\frac{1}{3}} \left(\frac{\sigma^k}{\sigma^{k+1}} \right)^{+\frac{1}{3}} d_s^k, \quad (77)$$

where k is the temporal iteration and the total sinuosity can be used as a proxy of the length of the river.

While the constancy of the floodplain slope seems a reasonable hypothesis, it will be clear in section 3.1 that it does present some issues. In particular, it does not consider changes in the sediment transport capacity that arise from the change in river slope and which could actually influence the evolution of the bankfull geometry.

To solve this issue Li et al. (2015) proposed an empiric correction for the Shields stress that was used in Eke, Parker, and Shimizu (2014) for a constant curvature solution and in Eke, Czapiga, et al. (2014) for the solution with an arbitrary distribution of curvature. Moreover, they also included the width evolution, which is something that is often missing in these meandering evolutionary models. Unfortunately, their approach still shows a decrease in the transport capacity and the introduction of the width evolution led to a decrease in width that is not observed in real rivers, as showed by Monegaglia and Tubino (2019) with satellite data.

2.1.5.1 MT approach

The Monegaglia and Tubino (2019) approach (MT approach) was derived to solve the problem they found in the existing models. They propose to describe the width variation with an adaptation of Equation 7 proposed in Monegaglia et al. (2019), while for the update of the bankfull geometry, they introduce a physically based approach, derived from the

Exner equation.

Monegaglia et al. (2019) proposed to use Equation 7 under the hypothesis of two independently moving banks. They write that the erosion rate for the single bank $\zeta^*|_{\pm B^*}$ can be written as

$$\zeta^*|_{\pm B^*} = \pm 2E (U^*|_{\pm B^*} - U_R^*), \quad (78)$$

where U_R^* is a reference value for the velocity. From this it is possible to obtain the equations for the dimensional erosion rate and for the dimensional width rate change as

$$\zeta^* = \frac{1}{2} (\zeta^*|_{+B^*} + \zeta^*|_{-B^*}) = E (U^*|_{+B^*} - U^*|_{-B^*}), \quad (79)$$

$$\frac{d2B^*}{dt^*} = \xi^* = \frac{1}{2} (\zeta^*|_{+B^*} - \zeta^*|_{-B^*}) = E (U^*|_{+B^*} + U^*|_{-B^*} - 2U_R^*). \quad (80)$$

Equation 7 can be derived from Equation 79 using the uniform flow velocity as reference value and as scaling. When using the decomposition in Equation 36 with antisymmetric U , Equation 80 can be rearranged finding

$$\frac{dB}{dt} = E(U - 1). \quad (81)$$

Looking at the resulting equation, it is apparent that only a change in the bankfull geometry can affect the width in this formulation and the only way a perturbation of the flow field can affect the width is by introducing the symmetric term, as proposed by Frascati and Lanzoni (2013) and Luchi et al. (2011).

In the original article an update for the river bed slope (S) was derived for the single meander. However, in this PhD study the focus is on longer stretches of rivers, composed of several meanders. To adapt the MT approach to longer domains while maintaining the local nature of the equation, it is necessary to subdivide rivers in multiple reaches. The debate for the length of these reaches is still open, however it was decided to use the bend division, since it allows for a simpler description of their moving boundaries, being always

defined by the bend inflection points. The resulting equation is also slightly different from the original one, to account for the incoming sediments from the upstream reaches.

As in the original formulation the equation is derived from the Exner equation, that can be written as

$$(1 - p_b) \frac{\partial \eta^*}{\partial t^*} + \frac{\partial q_{s,s}^*}{\partial s^*} + \frac{\partial q_{s,n}^*}{\partial n^*} = 0 \quad (82)$$

with the bed porosity (p_b). The equation is then averaged on a cross-section, which requires defining the flux of sediment in the transversal direction caused by a change in the river width as

$$q_n^*|_{\pm B^*} = -\frac{\partial B^*}{\partial t^*} \cdot \hat{n}_{\pm B^*} D^* (1 - p_f) = \mp (1 - p_f) D^* \frac{\partial B^*}{\partial t^*} \quad (83)$$

with the floodplain porosity (p_f) and knowing that $\hat{n}_{\pm B^*} = (0, \pm 1)$. The resulting equation is then

$$(1 - p_b) B^* \frac{\partial \eta^*}{\partial t^*} + B^* \frac{\partial q_{s,s}^*}{\partial s^*} - (1 - p_f) D^* \frac{\partial B^*}{\partial t^*} = 0. \quad (84)$$

To consider the effect of the meander elongation, Equation 84 needs to be averaged over the chosen reach length, in this case a single bend of length L^* . Knowing the change in relief of the two inflection points of η^* , the river bed slope of the bend is defined as

$$\tilde{S} = \frac{\eta^*}{L^*}. \quad (85)$$

The resulting equation for the slope evolution can be written as

$$\frac{\partial \tilde{S}}{\partial t^*} = -2 \frac{\tilde{S}}{L^*} \frac{\partial L^*}{\partial t^*} + \frac{1}{L^{*2} B^* (1 - p_b)} (Q_{s,ups}^* - Q_s^*) + \frac{(1 - p_f)}{(1 - p_b)} \frac{2 D^*}{L^* B^*} \frac{\partial B^*}{\partial t^*}. \quad (86)$$

$Q_{s,ups}^*$ is the sediment discharge entering the bend from upstream, and it can be calculated as the upstream bend transport capacity, while Q_s^* is the transport capacity of the current bend, under the hypothesis that the bed has enough sediments to keep up with the changes in Q_s . The equation can be normalized using a reference value of the parameters of the

initial bend state for B , L , S and D , under the hypothesis of uniform flow. The time is normalized using the timescale for the planimetric evolution (T_f), defined as

$$T_f = \frac{B_0^*}{EU_0^*}. \quad (87)$$

It is also convenient to multiply and divide both terms by a reference value $\Phi(\tau_{*0})$, which can be chosen for instance as the river transport capacity coming from upstream the investigated stretch.

The resulting equation reads

$$\begin{aligned} \frac{\partial S}{\partial t} = & -2 \frac{S}{L} \frac{\partial L}{\partial t} + \frac{\sqrt{\Delta g d_g^{*3}} 2 B_0^* \Phi(\tau_{*0})}{E L_0^{*2} U_0^* \tilde{S}_0 (1 - p_b)} \frac{1}{B L^2} \left(B_{ups} \frac{\Phi(\tau_{*ups})}{\Phi(\tau_{*0})} - B \frac{\Phi(\tau_*)}{\Phi(\tau_{*0})} \right) \\ & + \frac{(1 - p_f)}{(1 - p_b)} \frac{2 D_0^*}{L_0^* \tilde{S}_0} \frac{D}{L B} \frac{\partial B}{\partial t}. \end{aligned} \quad (88)$$

Equation 88 can be further simplified defining a series of parameters. In particular, if the timescale for the bed evolution (T_b) is defined as

$$T_b = \frac{(1 - p_b) \tilde{S}_0 L_0^{*2}}{\sqrt{\Delta g d_g^{*3}} \Phi(\tau_{*0})}, \quad (89)$$

the ratio between the planimetric and bed evolution timescales (R_T) is defined as

$$R_T = \frac{T_f}{T_b}. \quad (90)$$

G_0 is defined as

$$G_0 = \frac{\lambda_{m0}}{\pi \beta_0 d_{s0} \tau_{*0} \Delta}, \quad (91)$$

and r_p is defined as

$$r_p = \frac{(1 - p_f)}{(1 - p_b)}. \quad (92)$$

The final equation is then

$$\frac{\partial S}{\partial t} = -2\frac{S}{L}\frac{\partial L}{\partial t} + 2R_T\frac{1}{BL^2}\left(B_{ups}\frac{\Phi(\tau_{*ups})}{\Phi(\tau_{*0})} - B\frac{\Phi(\tau_*)}{\Phi(\tau_{*0})}\right) + 2r_pG_0\frac{D}{LB}\frac{\partial B}{\partial t}. \quad (93)$$

Using a reference condition as zero-condition instead of the parameters of the upstream bend allow for a simple representation of the parameters of the equation, in particular R_T . To solve this equation, it needs to be paired with Equation 81, with a uniform flow relationship

$$U = \sqrt{\frac{C_{f0}}{C_f}}DS \quad (94)$$

and with the continuity equation for the liquid phase

$$BDU = 1 \quad (95)$$

under the hypothesis of constant liquid discharge. Finally, to evaluate the elongation of the bend, this system of equations has to be paired with a meandering river evolutionary model, such as the periodic one described in section 2.1.4.4.

A particular relevance in Equation 93 is held by R_T . As described in Monegaglia and Tubino (2019), high values of R_T means that the river bed slope is adapting faster than the planimetric evolution and vice versa. This entails that at the upper limit of R_T (around $\sim 10^1$) the river bed is adapting instantly to changes in the planimetric configuration, ultimately keeping the river bed slope and the bankfull geometry constant. On the other end of the spectrum ($R_T \sim 10^{-1} \div 10^{-2}$) the planimetry evolves so fast that the river bed slope cannot keep up, leading to a behaviour of the bankfull geometry close to what Equations (75-77) describe, at least when keeping the width constant.

The term in the equation that contain Φ are also fundamental, because it describes the effects of the changing transport capacity and slope on a reach and on its neighbouring reaches. When the slope changes in a reach, due to the elongation or a cutoff, its trans-

port capacity will change accordingly, affecting also its downstream reach. This would create an imbalance between the incoming sediment supply and the transport capacity in that reach, leading to the deposition of the excess sediments or erosion of the missing sediments. As a result of the degradation or aggradation process, the slope will be affected, with a process that is key to understand the response of a reach to the slope to variations of neighbouring bends. This mechanism can be defined as one-dimensional morphodynamic influence, similarly to the two-dimensional one caused by the curvature and described in section 2.1.4.5. The introduction of this feedback mechanism ultimately allows for a more realistic description of the evolution of meandering rivers. Moreover, it can also be used to describe the effects of changes of the bankfull geometry caused by external stressors, such as human activities or climate change. A decrease or an increase of sediment supply, but also the effects of a human induced cutoff or a change in the profile of the river bed, could be easily modelled with the new approach.

The MT approach system of Equations was originally solved for a periodic solution with an Adam-Bashforth-Moulton numerical method, because Equation 93 is particularly tricky to solve, however this method seemed to work well. The same method was employed also throughout this PhD work, using a Fortran implementation, which can be found on GitHub¹. The results of the addition of MT approach to a simplified evolutionary model for meandering rivers with an appropriate periodic solution are reported in chapter 3.

2.1.6 Bogoni et al. (2017) model overview

In this manuscript, the tedious task of developing a model from scratch was avoided by choosing to use the Meander Centreline Migration Model (MCMM) developed by Bogoni et al. (2017). The choice was made because the model is quite complete, well documented, easy to modify to suit possible evolutions of the modelling approach and it is freely available on GitHub². In Bogoni et al. (2017) the reader will find a more complete overview

¹<https://github.com/jacobwilliams/ddeabm>

²<https://github.com/FluidMechanicsUNIPD/Meander-Centerline-Migration-Model>

of the model and its capabilities, but here are synthesized some of the key features that are important in the use cases presented in this manuscript.

Firstly, the ZS flow field solution is implemented in the model, which is the preferred solution as described in section 2.1.4, and so it is the erosion law in Equation 7. As described in section 2.1.5, the parameter update used is the one described in Equations (75-77), which presents some issues as anticipated. However, it is still widely used and the hypothesis of the constancy of the floodplain slope is not that far off reality, even though it is not perfect. For that reason, in this manuscript the analysis presented in chapter 3 started from the original model, setting also a baseline for any improvement employed. The model also features spatially variable erodibility, associated in particular with the presence of abandoned oxbow lakes and point bars associated with cutoffs, and the capability of introducing the presence of the valley boundaries to model confinement.

As explained earlier in section 2.1.3 the modelling of the cutoff processes is not always easy, but it is vital for the representativeness of the model. In MCMM the cutoff happens

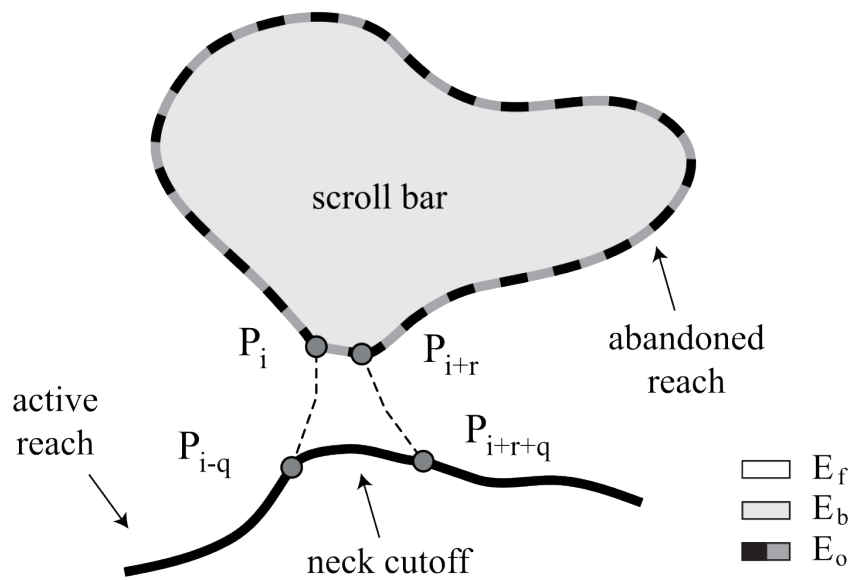


Figure 9 – Cutoff as modelled in MCMM, with the removal of points before and after the actual cutoff to better reconstruct the river axis. The figure is part of Figure 2 of Bogoni et al. (2017)

when two non-consecutive points (the minimum distance between two points can be set by

the user) get close enough (this distance can also be set by the user). A number of points (also set by the user) are then removed, before and after the cutoff, as displayed in Figure 9, and the axis is reconstructed with a resampling algorithm. This reduces the effects of the local high curvature that would probably lead to an unreasonably high migration rate.

The input needed by the model are the four non-dimensional parameter that define the bankfull geometry, assuming the sediment density is constant, so the aspect ratio (β), the Shields parameter (τ_*), the relative roughness (d_s), and the Reynolds' particle number (R_p). Furthermore, it needs the erodibility coefficient (E), a choice of resistance and sediment transport formula and an initial planimetry. The initial planimetry is often set as straight with a small perturbation and this was also the approach followed in this PhD thesis for most of the simulations.

2.2 Satellite data extraction and PyRIS

Satellite data are becoming ubiquitous in the study of the Earth morphology and in particular for rivers, thanks to the capability of observing remote areas and to the relatively short intervals between subsequent images and relatively long period of observations (40 years for the Landsat mission³) (Sylvester et al., 2019). There are a plenty of different approaches and software that take advantage of this enormous potential for the study of meandering rivers (Constantine et al., 2014; Rowland et al., 2016; Schwenk et al., 2017; Speed et al., 2024) and among these one that stands out is Python-Rivers from Satellite (PyRIS), developed by Monegaglia et al. (2018).

2.2.1 PyRIS

Python-Rivers from Satellite (PyRIS) is specifically designed for the automated extraction of meandering rivers from satellite imagery, it is open source and it is written in Python⁴. It is both a software that can be used from the command prompt and a python

³<https://landsat.gsfc.nasa.gov/>

⁴<https://www.python.org/>

package.

As Monegaglia et al. (2018) describe, PyRIS is a process-based software that enables for the automatic extraction of meandering rivers centrelines and can evaluate their migration. Compared to other available tools, such as those developed by Schwenk et al. (2017) or Rowland et al. (2016), PyRIS has the advantage of being fully open-source and written in an open-source language. Furthermore, as it is a Python package, it can easily be integrated into other softwares and scripts. It is able to compute the masks internally, using a combination of different indexes, and requires little input from the user, allowing for a more streamlined process and increasing the efficiency of the analysis. Lastly, its ability to automatically track the bend migration and the bar dynamics makes it a very powerful and versatile tool for analysing meandering rivers.

Starting from Landsat data, it extracts the river binary masks using radiometric indices that can detect water, vegetation and exposed sediments from multi-spectral imagery. The user can choose what indices to use, but the default setting is a combination of these three:

- Normalized Difference Vegetation Index (NDVI);
- Modified Normalized Difference Water Index (MNDWI);
- Short Wave InfraRed Band (SWIR).

The binary mask is then cleaned from small objects and then PyRIS identifies the features in the mask that can be chosen for analysis. The user can decide to do this choice manually or through an automated process and, after that, the mask for the analysis is saved. Following the mask generation, the software proceeds to skeletonize it, simplifying the mask to a single pixel skeleton, that has as attribute the local width of the mask. Through the use of a pruning algorithm, shorter branches are removed and the skeleton is then saved. The axis is extracted from the skeleton and every time there is a bifurcation of the main channel, one of the two is chosen depending on the width and length of each channel. The axis is then interpolated with a cubic spline with points spaced every eighth of the river width and

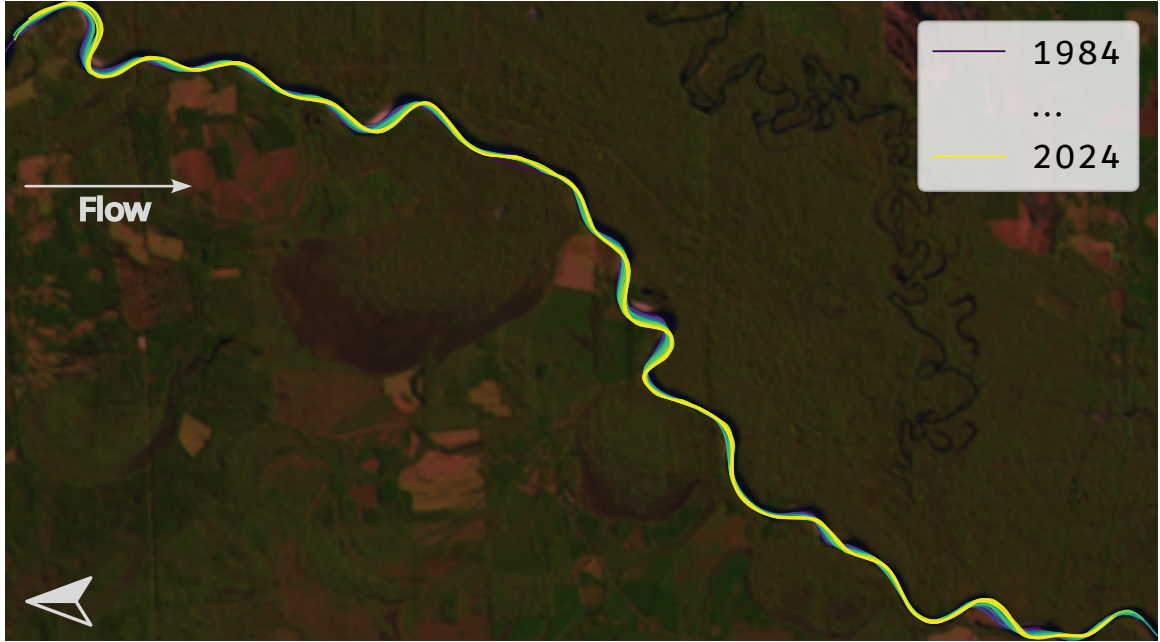


Figure 10 – Example of an analysis performed with PyRIS on the Sabine River, at the border between Texas and Louisiana (US). The coloured lines, ranging from purple to yellow, are the river centreline in the period between 1984 (purple) and 2024 (yellow), one for each year. The background is the combination from the Red, Green and Blue bands of the Landsat 5 image collected on 30th November 1984.

filtered with a Savitzky–Golay filter. The saved file contains the x and y coordinates, the angle between the tangent to the centreline and the x -axis (θ), the curvature ($\mathcal{C}$), the half width (B). When multiple axis are available, PyRIS is able to evaluate the migration using the curvature and the inflection points to correlate the same bends in different years. PyRIS can also detect bars and track their migration using the SWIR index.

In Monegaglia et al. (2018) the reader will find a better insight on the capabilities of the software and the design choices of the original version, in particular on the correlation of the curvature for the evaluation of the migration and the bar dynamics. In Figure 10 is reported an example of the axis extracted with PyRIS for the Sabine River.

Although the original version was already revolutionary, there was room for improvement to add new features and fix some existing issues. In particular, during this PhD work were addressed the following ones:

- PyRIS was written with Python 2, however the use of the older version of Python is

rather limiting and it is also now deprecated;

- the original version of the software did not come with an instruction manual except for a brief excerpt in Monegaglia et al. (2018);
- with images from Landsat 8 and 9 missions, there were some issues in the mask extraction when using the complete mix of indices that was included in the code;
- the mask extraction process has been done locally and it is the most resources consuming process both in terms of RAM, for the actual process, and storage, for the all the images;
- PyRIS only worked on Landsat data, which have the longest time span across multi-spectral images, but do not have the highest resolution both spatially and temporally.

Firstly, the code was converted to Python 3, to avoid using virtual environments and older packages. This improved understanding of how the code behaves, making it easier for other members of the scientific community to use it, helping with error detection and collecting ideas for improvements. It also prompted to the writing of a first revision of the manual distributed with the code. While it could be improved further, it already makes the installation and operational procedures easier to understand. The most up-to-date version of the PyRIS software and of the manual are freely available on GitHub⁵.

Regarding the issues with Landsat 8 and 9 images, they only arise when using the complete mix of indices and it was caused by the increased bit depth of the images in the latter generations of Landsat (from 8 bit in the Landsat 4, 5, and 7 to 16 bit in Landsat 8 and 9). PyRIS uses the Otsu thresholding algorithm (Otsu, 1979) for the MNDWI and NDVI, that chooses a threshold based on the natural breaks in the pixel distribution of each image, and so it will not be affected by a change in the values between different images, because the threshold is set uniquely for the analysed image. However, for the SWIR index,

⁵<https://github.com/riccardobonanomi/pyris3>

used to identify exposed sediments deposits, PyRIS uses a threshold that was calibrated for Landsat 4, 5, and 7, and so it had to be rescaled for the use with Landsat 8 and 9.

Finally, for the last two issues, the most effective solution was to add into the software the capability to load pre-processed masks from external sources. With some adaptation of the code, PyRIS is now able to take a `TIF` file binary mask, import it, apply all the cleaning steps that are used for the Landsat images and choose automatically or let the user choose the features contained in the mask. After that a PyRIS mask file is created and the code works as it would with Landsat images, with the exception of the bar extraction and tracking, since it needs to recalculate the SWIR index and at the present time this is not yet adapted to take it from external sources. With this modification the process is extremely less resource and storage intensive, since the folder containing the all the data for a single Landsat acquisition can be as big as a 1 GB, while a `TIF` binary mask is only a few KB. This clearly only makes sense if the mask segmentation process is moved away from the local machine, but in recent years the development of Google Earth Engine (GEE) has allowed for extremely powerful cloud based computations (Boothroyd et al., 2021) that are the perfect match to the evolution proposed here for PyRIS as it will be described below.

2.2.2 *Google Earth Engine and PyRIS*

Google Earth Engine⁶ combines an enormous catalogue of multi-spectral satellite data from multiple sources with the capability of performing complex calculations and operations on said catalogue. The updated PyRIS, with binary masks generated using GEE, allows for lighter and smoother operations and also for more flexibility in the mask extraction, as described below. Moreover, the analysis can also be extended to others sources of satellite data, such as Sentinel-2⁷, allowing for more accurate calculations, albeit for shorter time spans.

⁶<https://earthengine.google.com/>

⁷https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2

2.2.2.1 Permafrost river analysis

In particular, during this PhD work an analysis on meandering rivers flowing in permafrost covered floodplains and their difference with non-permafrost rivers was performed using PyRIS and a GEE code and it was published in Ragno et al. (2024). The GEE code used in this project is available on GitHub⁸ and it was developed with Dr. Marta Crivellaro⁹ starting from the code proposed in Crivellaro, Vitti, et al. (2024) to extract binary masks from Landsat data.

Other than the clear superiority in performance described in section 2.2.1, the advantage of using an external mask extraction in this case was the ability to modify the process to better fit the needs of the specific research. In particular the summer envelope was used for the analysis, instead of using a single image per year, because it allowed to reduce noise in the mask, using the entire season in which these rivers are active and the soil is mostly clear by snow (May to September). Moreover, to further reduce noise related to the permafrost features, such as thermokarst lakes and mud boils, the Perona-Malik anisotropic filter (Perona & Malik, 1990) was applied before the Otsu thresholding (Otsu, 1979), to remove all the small and medium-sized spatial features and ultimately to provide a cleaner binary mask and streamline the subsequent feature selection in PyRIS. For a more in-depth description of the mask extraction process the reader can explore the Supplementary Information of Ragno et al. (2024).

The GEE code was further modified after a first revision of the work to add the extraction binary masks from Sentinel-2 imagery, for accuracy testing, particularly in narrower river, that were on the edge of what would be considered measurable with Landsat data as described in Monegaglia et al. (2018). They suggest considering rivers larger than 3 Landsat pixels at least, so larger than 90 m. In this study however, the analysis of the variability of the width was a key element and so this comparison allowed to double-check the validity

⁸https://github.com/marta-cri/HYMO_trajectories/tree/Arctic_rivermasks_serviceaccount

⁹Department of Civil, Environmental, and Mechanical Engineering, University of Trento, Trento, Italy

of the Landsat results, which will be discussed in section 3.4.

2.3 Field data

Satellite data give a powerful insight on rivers, their evolution in time and can help access remote areas, and some attempt have been made to determine solid and liquid discharge from satellite imagery (Aires et al., 2022; Bjerklie et al., 2018), but to characterize accurately the bankfull geometry of a river there is still a need for in situ measurements. There are plenty of already published datasets (Parker et al., 2007; Ragno et al., 2022; Wilkerson & Parker, 2011), but in particular the Lagasse et al. (2004) one stands out for meandering rivers and it will be described in section 2.3.1. Moreover, to accommodate the specific needs of this PhD project, a field measurements campaign has been carried out on the Sabine River, on the border between Texas and Louisiana in the United States, as described in section 2.3.2

2.3.1 *Lagasse et al. (2004) database*

The Lagasse et al. (2004) database was assembled under the National Cooperative Highway Research Program¹⁰ by the Transportation Research Board¹¹, to assess river migration and the dangers that it poses for transportation infrastructures.

The dataset contains hundreds of meandering bends from the 89 meandering river in the US with data collected at different years. The meander bends are subdivided in classes defined with a modified version of the classification proposed by Brice (1975) that can be found at page 16 of Lagasse et al. (2004). The planimetric features and the migration were evaluated through the use of manual recognition on areal photogrammetry, with some computer assisted techniques, and they were paired with bankfull geometry data. Their dataset is extremely helpful due to the fact that it has extensive bankfull geometry data that are not often easy to find and they are well-ordered in tables that are easy to work with,

¹⁰<https://www.trb.org/NCHRP/>

¹¹<https://www.nationalacademies.org/trb/transportation-research-board>

both in an automated and manual way. The data were used to set a baseline for parameters of the simulations in section 3.1 and to compare the results to them. The dataset was kindly provided by Federico Monegaglia, together with some pre-processing codes, that were used in Monegaglia et al. (2019).

2.3.2 *Sabine River*

The field measurements survey on the Sabine River has been carried out during a two-months visiting period at the Department of Geography & Anthropology¹² of the Louisiana State University (LSU) in Baton Rouge, Louisiana (US) under the supervision of Dr. Kory M. Konsoer and with the help of Dr. Eddy Langendoen, Michael E. Ursic and Jacob A. Ferguson from the Watershed Physical Processes Research unit of the National Sedimentation Lab of the USDA-Agricultural Research Service (USDA-ARS) in Oxford, Mississippi (US)¹³.

The main idea behind the survey was to identify a meandering river stretch comprising at least one sinuous reach and one straighter reach, with the ultimate goal of comparing their behaviour with the theoretical findings of Monegaglia and Tubino (2019). These particular conditions, in a river that was large and deep enough to be able to perform measurements with boat-mounted instruments, were found in a stretch of the Sabine River, just 1.5 km east of Belgrade, Texas (US).

The Sabine River has a drainage area of around 25 267 km², of which just over a quarter is downstream the Toledo Bend reservoir, and most of the lower stretch of the river coincides with the border between Texas and Louisiana. The river flows through a variety of environments, but the lower part is a humid subtropical coastal plain setting and at its estuary it flows into the Sabine Lake which is connected to the Gulf of Mexico. The Toledo Bend reservoir was completed in 1967, it has a capacity of over $5.5 \cdot 10^9$ m³ and it is primarily used for hydropower generation and it is not operated as flood control

¹²<https://www.lsu.edu/ga/>

¹³<https://www.ars.usda.gov/southeast-area/oxford-ms/>

(Phillips, 2003). While the presence of the dam has an impact on the downstream reaches, (Phillips, 2003) showed that the erosion wave gets damped rapidly and the lower portion of the river seems mostly unaffected, with clear signs of in-channel and on-the-floodplain deposition, channel migration and in general morphological activity consistent with what the non dammed tributaries show. They concluded that the Sabine River most likely was and still is transport-limited and so the reduction of the sediment supply from upstream did not influence the river dynamics as much. Moreover, they showed how, even if the hydrological regime is affected by the high variability of the outflow of the power plant, these effects are almost negligible already after 30 km downstream the dam and they suggest that the dam release pattern is close to what to the pre-dam flow, at least on the longer time scales.

2.3.2.1 Survey site description

The reach chosen for the analysis is a stretch located 1.5 km east of Belgrade, Texas (US). It is just under 11 km long and that starts around 8 km downstream the bridge of Highway 190 connecting Bon Wier (Texas) and Merryville (Louisiana). The reach, that can be seen in Figure 12, was chosen because it has a straighter reach, followed by some more sinuous bends and then another straighter reach. As mentioned earlier, Phillips (2003) noted that this reach can be considered unaffected by the presence of the Toledo Bend reservoir. The river average width in this stretch is around 130 m, so it is wide enough for analysis with Landsat data to evaluate the evolution and the migration through PyRIS. Moreover, on the aforementioned bridge there is a hydrometer managed by the Sabine River Authority¹⁴ and by the USGS¹⁵, whose data can be found at <https://waterdata.usgs.gov/monitoring-location/08028500/>.

The measures were performed on 15th and 16th May 2024. During the survey period the average water stage measured by the hydrometer was around 10.4 m, corresponding to a

¹⁴<https://www.sratx.org/>

¹⁵<https://water.usgs.gov/networks/fps/>

flow discharge of around 1200 m^3 , and, as it can be seen in Figure 11a, it was quite constant through the whole survey, with a variability of the stage of just the 0.6%. This flow stage for the Sabine River is considered by the NOAA¹⁶ as moderate flood, that correspond to “some inundation of structures and roads near streams. Some evacuations of people and/or transfer of property to higher elevations are necessary.”¹⁷, which would fit the observation performed on the river, that revealed conditions mostly close to the bankfull ones.

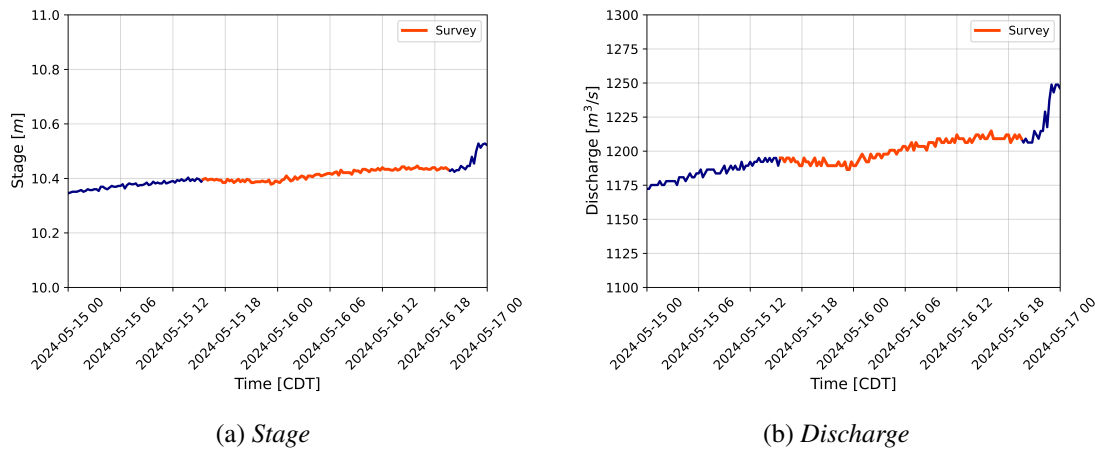


Figure 11 – Stage (a) and discharge (b) of the Sabine River measured at the Bon Wier, Texas (US) hydrometer between the 15th and 16th May 2024. In orange is shown the period between the start and the end of the survey, which can be considered quite constant, with a variability for the stage of around 0.6% of the average value of 10.4 m and for the discharge of around 2.4% of the average value of $1200 \text{ m}^3/\text{s}$. Data available at <https://waterdata.usgs.gov/monitoring-location/08028500/> ©USGS.

2.3.2.2 Measurements

The measurements were performed with two manned boats, one from LSU and the other from USDA-ARS. The LSU boat was used for flow field measurements and bed sediment sampling, while the USDA-ARS was used for the bathymetric survey.

Flow field measurements The flow field measurements were performed using the Tele-dyne WorkHorse Rio Grande¹⁸ 1200 kHz Acoustic Doppler Current Profiler (ADCP), which

¹⁶<https://water.noaa.gov/>

¹⁷<https://www.nssl.noaa.gov/education/svrwx101/floods/faq/>

¹⁸https://www.comm-tec.com/prods/mfgrs/RDI/brochures/rio_grande_ds_lr.pdf

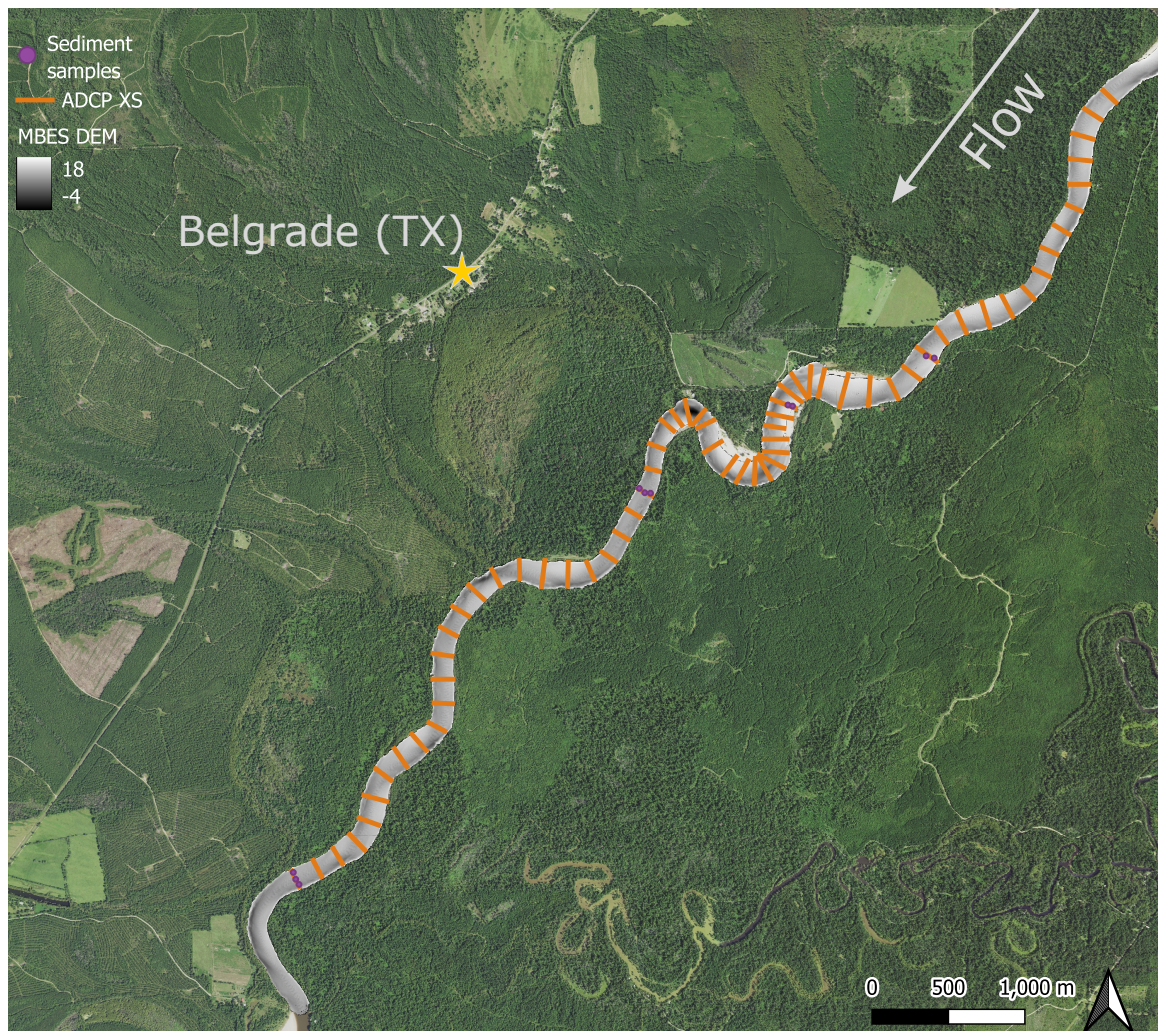


Figure 12 – Surveyed reach of the Sabine River, just 1.5 km East of Belgrade (Texas, US). The orange lines are the ADCP cross-sections (XSs), the purple points are the sediments samples collected and the gray-scale map is the MBES bathymetric survey. The background map is the NAIP ortophoto from 2022 ©USDA.

has a 4-beam transducer. The ADCP emits acoustic signal at a know frequency and it measures the backscattered signal produced by particles moving with the water and the Doppler shifts caused by the velocity of these particles. Under the assumption that these particles are moving the with the water, the measured backscatter is transformed in a three-dimensional flow field (Parsons et al., 2013). The data were collected and pre-processed with the WinRiver II¹⁹ software from Teledyne that also connects to a Global Navigation Satellite System (GNSS) antenna to track the ship and sensor movements. For each XS,

¹⁹<https://hydroacoustics.usgs.gov/movingboat/WinRiverII.shtml>

four transect were measured, two in each direction, and they were then averaged out using the Velocity Mapping Toolbox (VMT) developed by Parsons et al. (2013) in Matlab²⁰. This software averages and interpolates the various transects together to obtain a single XS, taking into account the path of the boat in each pass to account for course deviation caused by the flow. It is also useful in the analysis of the results, being able to plot easily each single cross-sections (XSs) and an overview map of all the XS, with the corresponding velocities. During the two days of survey, 67 XS were collected, for a total of 268 transects. The XS were spaced every half river width in the sinuous section, while in the straighter sections they were spaced every river width, because the variability in the flow was far less pronounced. The position of all measured XS is plotted in Figure 12.

Bathymetric survey The bathymetric survey was performed using a Norbit Wideband Multibeam Sonar (iWBMS)²¹, which is composed by an MultiBeam Echo Sounders (MBES) and a dual GNSS antenna Applanix POS MV WaveMaster II²². An MBES works by emitting a fan-shaped acoustic impulse and measuring the time it takes for the signal to reach the sensor again. Knowing the speed of sound in water (based on various parameters, such as temperature), it can calculate the distance to the riverbed and create a point cloud. GNSS antennas are used to determine the instrument's exact position and orientation, which is essential for creating an high-resolution bathymetry. The boat makes a few parallel passes to collect the data, while the operator can see the data in real time and correct the trajectories as necessary to fill in any blank spots where vegetation and other disturbances might hinder data collection. Moreover, the impulse can also be oriented laterally to better survey the river banks or any other shallow-water features. Once the point cloud has been collected, it is cleaned using specific software (HIPS and SIPS²³ in this case) to remove unwanted noise, ghost responses and other disturbances, such as trees. Finally, a digital elevation

²⁰<https://it.mathworks.com/products/matlab.html>

²¹<https://norbit.com/subsea/products/ps-120006-24.iwbms.a4/>

²²<https://www.str-subsea.com/products/applanix-pos-mv-wavemaster-ii-system/>

²³<https://www.teledynecaris.com/en/products/hips-and-sips/>

model (DEM) can be interpolated at the desired resolution, as shown in Figure 12.

At the end of the survey, five repetitive passes were performed at 15 minutes interval in a shorter straighter section with the presence of bedforms to collect the data to estimate the solid transport through the ISSDOTv2 method (McAlpin et al., 2022, 2023). This method was developed by the US Army Corps of Engineers (USACE)²⁴ and allows for the evaluation of the sediment transport through the tracking of bedform movements in repeated high resolution bathymetries.

Sediment sampling Sediment sampling from the bed of the river has been performed in 10 different locations along the river, as showed in Figure 12. Three samples were collected at the last XS, after the second less sinuous reach, another three were collected at the XS at the end of the last bend in the sinuous section and the last four were collected on the bars in the bends of the sinuous section, in two different XSs. Where 3 points per XS were collected, the points were more or less spaced evenly across the whole width of the river, while were only two were collected, it was close to the inner bank and the centre, since the river was too deep to collect sediment in the outer bank.

The sediment samples were collected with a BMH-60 Sediment Sampler²⁵ from the USDA-ARS. The sampler is attached to a rope around 10 m long, it has a spring-loaded compartment at the bottom and it is shaped as a fish to reduce its drag, while remaining oriented with the flow and sink vertically, even in strong currents. It has to be lowered from the boat rapidly in order for it to reach the bed and penetrate it a few centimetres. After it stops in the bed, the rope looses tension and the spring-loaded compartment is released collecting a small sample of sediments. The compartment is not large, but, since it is designed for sand or finer particles, one or two samples per location are generally enough to characterize the grain size distribution. The samples were then oven dried and sieved at the LSU Fluvial Geomorphology Lab to obtain the grain size distribution for every

²⁴<https://www.usace.army.mil/>

²⁵<https://prph2o.com/bmh-60-sediment-sampler/>

location. In Table 1 are reported the main diameters and the position of each point, while in Appendix B are reported all the data collected in the sieving process. The sediments are generally medium sand with an average d_{g50} of around 0.4 mm, with some coarser sand in the downstream end and some fine and medium gravel mixed at the upstream end, that could have been transported by a small creek that was coming in around that area, even though the discharge seemed negligible.

Table 1 – Position (WGS 84 EPSG:4326) and main diameters for each point sampled during the field survey on the Sabine River.

	WP7	WP8	WP10	WP11	XS68L	XS68C	XS68R	XS116L	XS116C	XS116R
Longitude [°]	-93.6468	-93.6471	-93.6371	-93.6377	-93.6564	-93.6568	-93.6572	-93.6803	-93.6805	-93.6807
Latitude [°]	30.6714	30.6715	30.6743	30.6744	30.6662	30.6663	30.6665	30.6430	30.6433	30.6437
d_{05} [mm]	0.18	0.19	0.19	0.23	0.14	0.23	0.36	0.32	0.18	0.20
d_{16} [mm]	0.23	0.25	0.28	0.30	0.18	0.31	0.59	0.48	0.22	0.27
d_{25} [mm]	0.26	0.28	0.33	0.35	0.20	0.36	0.72	0.54	0.25	0.31
d_{50} [mm]	0.30	0.39	0.44	0.45	0.23	0.43	0.98	0.70	0.31	0.41
d_{75} [mm]	0.35	0.60	0.58	0.61	0.29	0.53	1.30	0.89	0.40	0.51
d_{84} [mm]	0.39	0.95	0.64	0.69	0.31	0.60	1.51	0.97	0.46	0.58
d_{95} [mm]	0.47	18.55	0.77	1.19	0.34	0.69	2.20	1.30	0.66	0.69

CHAPTER 3. RESULTS AND DISCUSSION

The following chapter contains the results of my PhD work and their discussion. In section 3.1, I present the relationship between the bankfull geometry and the planimetric configuration of meandering rivers, obtained with the MCMM model, while section 3.2 will be reserved to the description of the alteration of the bankfull geometry in meandering rivers caused by changes in the sediment supply. In section 3.3, I present the results of the analysis of the local update for the bankfull geometry parameters, performed with the Monegaglia and Tubino (2019) approach (MT approach). Finally, in section 3.4, I will discuss how permafrost affects meandering rivers evolution and how can we model its effect.

3.1 Bankfull geometry and planimetric configuration in meandering rivers

To properly understand how meandering river behave and how external stressors can affect them, the first step taken in this PhD project was understanding how the bankfull geometry of a river is related to its planimetric configuration, since, as stated before, this has often been neglected, but it can be key element to understand the effects of changes of said bankfull geometry. To do so, the MCMM model was first used, to investigate one hand its main characteristic and on the other hand to define a baseline for future model development, acknowledging also its limitations.

In this section are first discussed the simulation results and then they are compared to satellite data and the Lagasse et al. (2004) database to understand the model limitations. Each plot presented in this section for the model results will show a single entry per simulation, calculated as the temporal and spatial average of the steady state of that simulation, which will be introduced in the next section. Satellite data plots will show a single entry per river, spatially and temporally averaged too, unless stated otherwise.

3.1.1 Steady state definition

To carry out effective analyses on meandering rivers, it is important to define a bankfull condition that can be representative of the state of the river. As described by Camporeale et al. (2005) and in section 2.1.3, the elongation caused by the bar pull and bank push process is balanced by the shortening induced by cutoffs, keeping the river oscillating around a statistical steady state which is representative of the river behaviour.

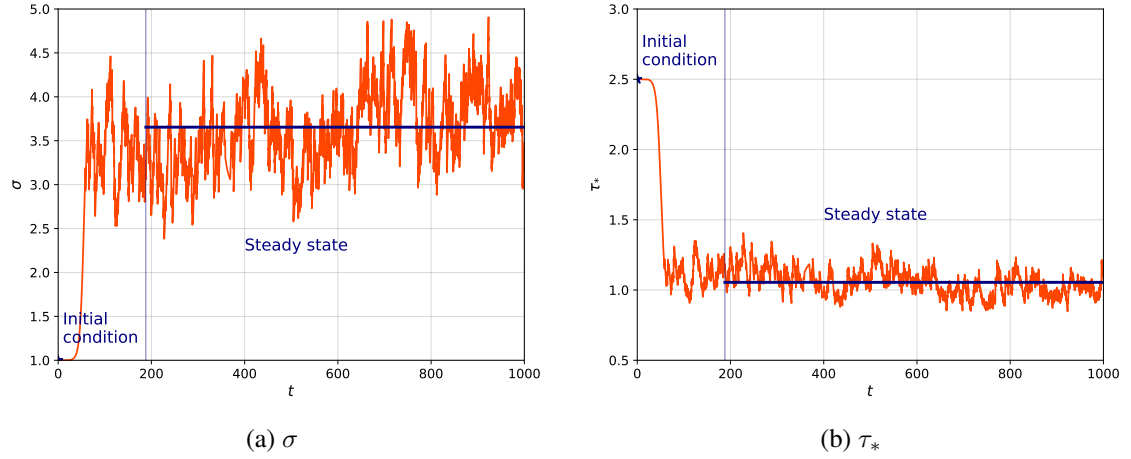


Figure 13 – Total sinuosity (σ) (a) and Shields parameter (τ_*) (b) courses during a simulation with the MCM initialized with a straight planimetry. The initial bankfull parameters for this simulation were $\beta = 25$, $\tau_* = 2.5$, $d_s = 7.5 \cdot 10^{-5}$ and $R_p = 20$. For this simulation the Engelund and Hansen (1967) resistance formula was used with the Wright and Parker (2004) correction for the dunes presence and their formula for sediment transport was used too. The average parameters of the steady state were $\beta = 16.4$, $\tau_* = 1.06$ and $d_s = 4.9 \cdot 10^{-5}$. The steady state was considered reached after 100 cutoffs, which is represented by the vertical blue line, to ensure the full development of the planimetry.

As described in section 2.1.6, the simulations are usually initialized with a straight planimetry and, due to the base flow update employed, a significant difference between initial and steady state arises. In the simulation shown in Figure 13, the total sinuosity (σ) (Figure 13a) increases steeply initially, causing the parameters of the bankfull geometry to decrease (Shields parameter (τ_*) in Figure 13b). After the initial phase, the stabilizing process described in section 2.1.3 begins, with the simulation oscillating around a fixed state. However, while one could wonder about which parameter to use when analysing the simulation, it is important to remember that the initial straight condition is only a modelling

artefact and it is not a part of the evolution of real meandering rivers. Hence, the only part of the simulation that is relevant to study is the steady state, which represent the behaviour of natural meandering river. To identify after how long this statistical steady state is reached in the simulations, it was decided to set a threshold on the number of cutoff occurred, after which the planimetric configuration was considered as fully developed. The threshold was generally set between 100 and 200 cutoffs and, as represented by the vertical blue line Figure 13, it seems that is effective in removing the initial sinuosity growth.

As explained above, the initial conditions are not relevant for the analysis of the simulations, but it is clear they have an impact on the final bankfull geometry and so it is paramount to make an accurate choice in their definition. Moreover, since one the focuses of this dissertation is the bankfull geometry, it was important to predict the output steady state beforehand, to be able to keep the simulations in a reasonable range of resulting bankfull geometry parameters. In order to do so, the average expected parameters for a simulation was defined using the Lagasse et al. (2004) database as a reference. With this choice, it was then possible to define the initial parameters using a first-attempt total sinuosity and reverting Equations (75-77). This approach is rather effective in the identification of the initial parameters, but up until now it was only used by Zolezzi, Luchi, and Tubino (2009), since previous study were generally not considering the bankfull geometry of the simulations as a main output. In Figure 14 it is reported an example of the distribution of the aspect ratio (β) of the Lagasse database in yellow, of the parameters chosen for the initial conditions in green and of the parameters of the steady state of every simulation in orange, and a similar plot could be provided for the relative roughness (d_s) and the Shields parameter (τ_*). It is quite clear that while the initial parameters are located towards the upper end of the Lagasse distribution, the steady state of the simulations are much closer to the Lagasse distribution, which confirms the effectiveness of the proposed method. It is also worth remembering that the goal of the simulations was not to recreate the distribution of the Lagasse et al. (2004) database, but to have a set of parameters that were represen-

tative of real meandering rivers and so in a reasonable range of values compared to the Lagasse et al. (2004) ones.

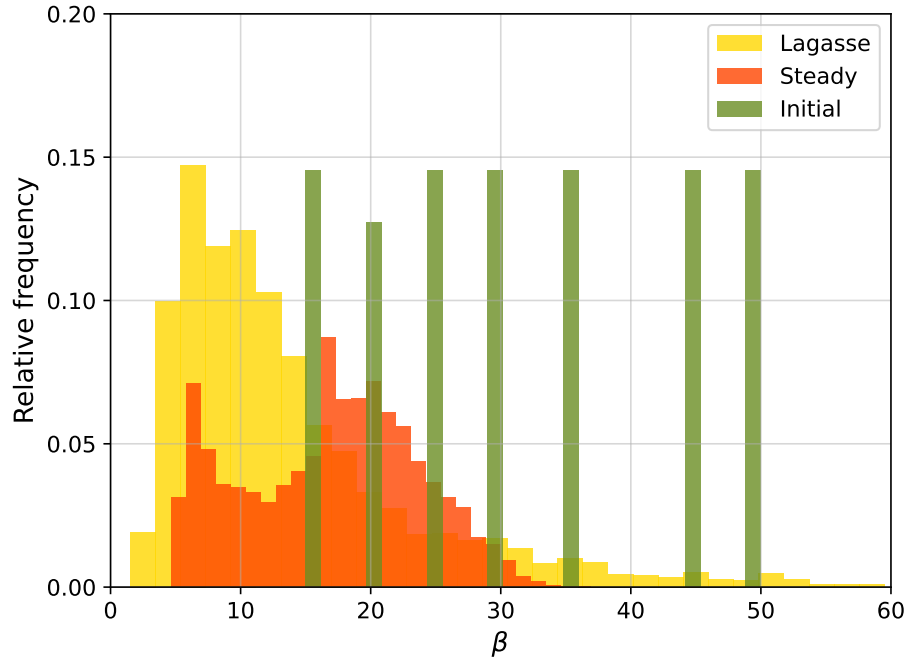


Figure 14 – Distribution of the aspect ratio (β) for a set of simulations of sand bed rivers. The yellow one is the distribution of the Lagasse parameters, the green one is the parameters chosen as initial parameters and the orange one is the distribution of parameters of the steady state of every simulation. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula and the Engelund and Hansen (1967) resistance formula with their correction for the dunes presence. All the parameters used for these simulations are found in Appendix C in Table 5.

To further understand how different the steady state and the initial condition are, the parameter space plot, represented in Figure 15, is of great help. In this plot the blue area represents the parameters ($\beta - \beta_R$ and τ_*) of the initial condition for a set of simulations, while the orange area represents the average parameters of the steady state from the same simulations. From the plot it is possible to see how much τ_* decreases during the initial phase of the simulation, but also how the regime of the simulation changes from the initial condition. The difference between β and β_R can be viewed as the distance of a simulation from the resonant condition and it highlights a big switch in the simulations regime, from mostly super-resonant initial conditions to steady states that range from sub-

to super-resonant conditions. As described in section 2.1.4, the two regimes are profoundly different, and thus, the choice of parameters that characterize the results can affect greatly their interpretation.

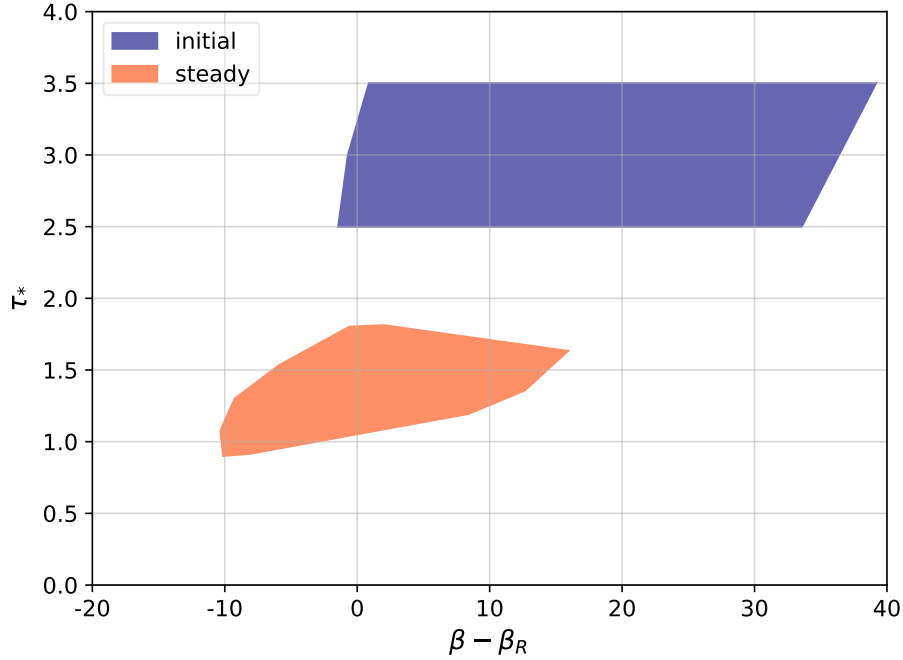


Figure 15 – Parameter space plot of the distance from the resonant condition ($\beta - \beta_R$) and Shields parameter (τ_*) for a set of simulations of sand bed rivers. The blue area represents the parameters of the initial condition, while the orange area represents the parameters of the steady state. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula and the Engelund and Hansen (1967) resistance formula with their correction for the dunes presence. All the parameters used for these simulations are found in Appendix C in Table 5.

3.1.2 Relationship between the planimetric configuration and the bankfull geometry

The next step is the delineation the relationship between bankfull geometry and planimetric configuration. There are various metrics that could be used to describe the planimetric configuration of a river, but in this case three parameters were chosen: the bend skewing angle (ψ), the bend sinuosity (σ_{bend}) and the total sinuosity (σ). The first two describe the behaviour of the single bends, while the last one gives an idea of the overall complexity of the entire reach analysed, giving a comprehensive picture of the characteristics of each

simulation configuration. Due to the higher presence of sand bed rivers, both in the rivers analysed with PyRIS and in the Lagasse et al. (2004) database, the analysis showed are mainly performed on sand bed rivers, but results for gravel bed rivers are reported at the end of the section, to show that the behaviour is similar to the sand bed ones.

Since the theoretical findings (Seminara et al., 2001) describe an expected behaviour for the bend skewing angle (ψ), this is the first parameter analysed. In particular, it was plotted against β minus β_R , which gives an idea on the distance between the steady state and the corresponding resonant condition. Since β_R is a function of τ_* and d_s , this difference is also a global indicator of the entire base flow and not just the aspect ratio. As it is shown

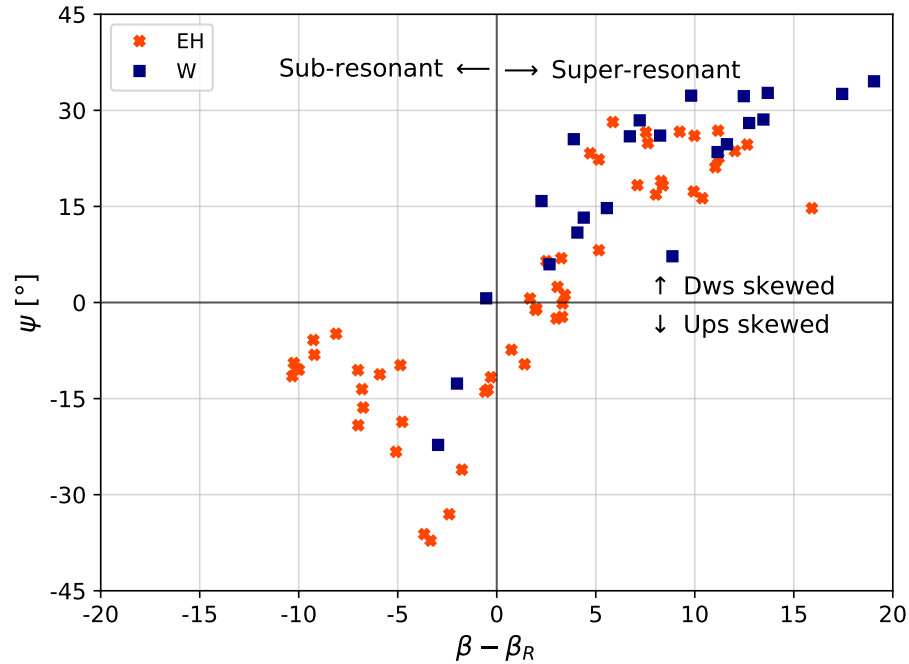


Figure 16 – Bend skewing angle (ψ) plotted against the distance from the resonant condition ($\beta - \beta_R$) for a set of simulations of sand bed rivers. As described in section 2.1.1, ψ is positive if the bend is skewed downstream and negative if it is skewed upstream. Each entry is the average in time and between bend for the steady state of a given simulation. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula and resistance formula with the different dunes correction. The orange crosses marked as EH are simulations performed using the Engelund and Hansen (1967) correction for the dunes presence, while the blue squares marked as W are performed with the Wright and Parker (2004) correction. All the parameters used for these simulations are found in Appendix C in Table 4 and in Table 5.

in Figure 16, the behaviour of ψ is consistent with the theoretical findings, with a general

preference of simulations in the sub-resonant regime for upstream skewed bend (negative ψ) and in the super-resonant regime for downstream skewed bend (positive ψ). This is not a surprise, since the ZS solution used in the model should and is able to detect the differences between the two regimes, however it is still a relevant test to validate the model. Moreover, the reader can distinguish two types of simulations in Figure 16: the orange Xs represent the simulations performed with the Engelund and Hansen (1967) dunes correction, while the blue squares represent the simulations performed with the Wright and Parker (2004) dunes correction. As show in Figure 8, the latter formula presents considerably lower β_R values and this entails a different position relative to the resonant condition even with the same base flow parameters. However, this does not seem to affect the position of the skewing points, as one would expect. In the plot it is readily apparent that the two results fit together well, demonstrating that the distance from the resonant conditions determines the resulting skewing angle regardless the initial condition and the value of parameters themselves. While this result is fairly easy to predict, it is still important to test this relationship, in particular because the skewing angle could then be used as a proxy of the regime of the river, for data the bankfull geometry is unknown. Thus, in the case of remotely sensed data, one could use the skewing angle to compare them to the model results, as it will be done in section 3.1.3.

While for ψ , the distance from the resonant condition was the obvious choice of parameter to compare with, for the bend sinuosity (σ_{bend}) various parameters could have been used. However, as it can be seen in Figure 17, σ_{bend} also displays a difference in behaviour between the two regimes, with generally higher sinuosity for the super-resonant condition. It is worth noting that this behaviour seems in conflict with the tendency of meandering bends to become more sub-resonant (Guo et al., 2019; Zolezzi, Luchi, & Tubino, 2009). However, when analysing the modelling results it is important to remember that the bankfull parameters are the same for the entire river, regardless the state of the individual bends. Hence, a single bend elongating will overall increase the total sinuosity, thus reducing the

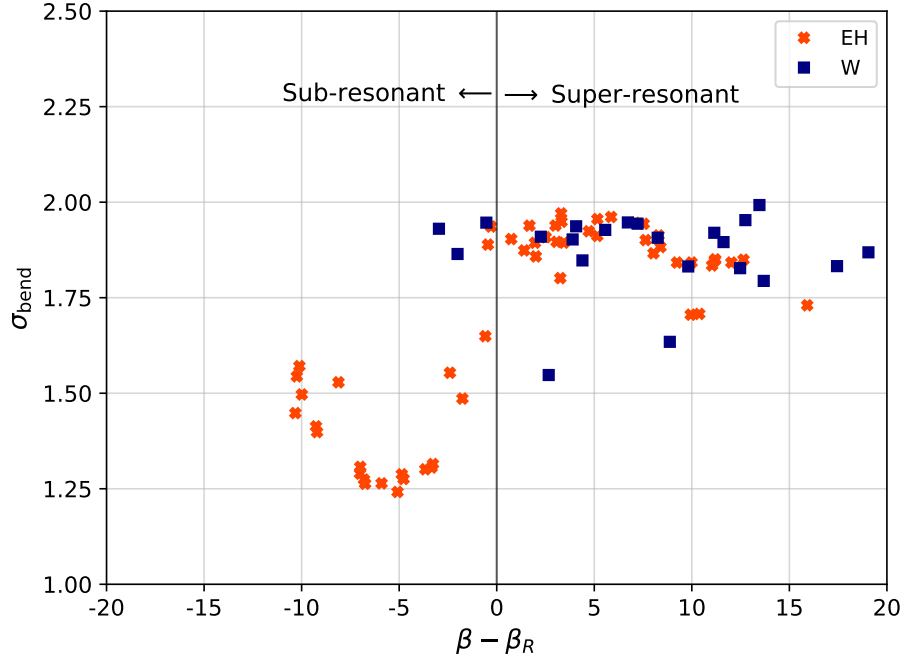


Figure 17 – Bend sinuosity (σ_{bend}) plotted against the distance from the resonant condition ($\beta - \beta_R$) for a set of simulations of sand bed rivers. Each entry is the average in time and between bend for the steady state of a given simulation. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula and resistance formula with the different dunes correction. The orange crosses marked as EH are simulations performed using the Engelund and Hansen (1967) correction for the dunes presence, while the blue squares marked as W are performed with the Wright and Parker (2004) correction. All the parameters used for these simulations are found in Appendix C in Table 4 and in Table 5.

aspect ratio, but this change will be drowned in the entire reach, leading to a far less evident change on the single bend. Moreover, since the regime of the river is either completely sub- or super-resonant, the comparison should be then performed only with fully sub-resonant or super-resonant reaches, because the model is not able to reproduce correctly the behaviour of single bends transitioning between the two regimes.

The last parameter analysed was the total sinuosity (σ), which gives an information on the overall complexity of the planimetric configuration of a reach, but it is also relevant because it is used for the base flow evolution, as described in section 2.1.5. In Figure 18 it is shown the behaviour of the total sinuosity (σ) per each simulation with the Shields parameter (τ_*), where it seems that the σ is increasing for lower values of τ_* . However, what it is shown in Figure 18 is a consequence of the relationship used to update the base

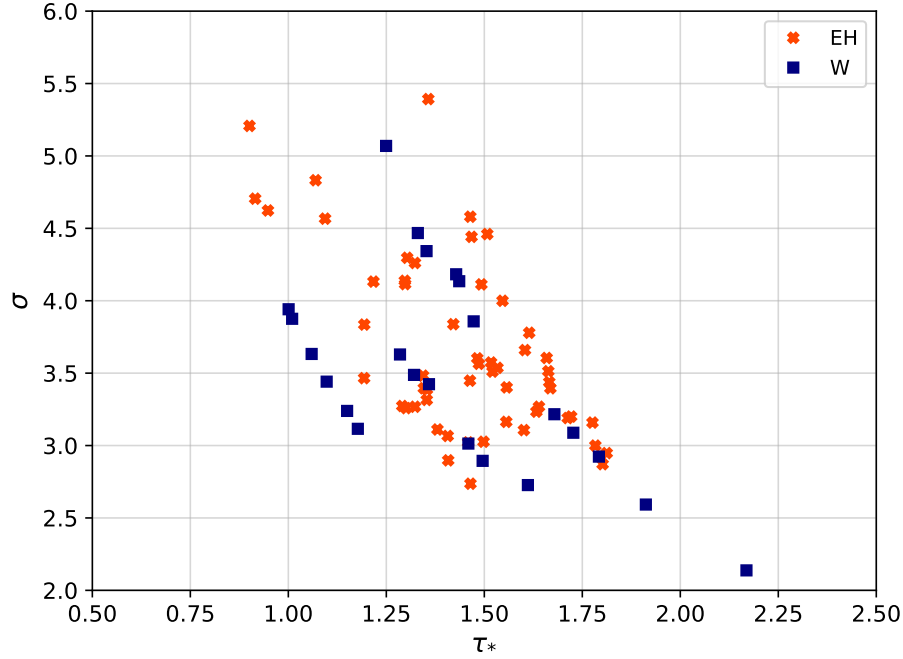


Figure 18 – Total sinuosity (σ) plotted against the Shields parameter (τ_*) for a set of simulations of sand bed rivers. Each entry is the average in time and between bend for the steady state of a given simulation. The orange crosses marked as EH are simulations performed using the Engelund and Hansen (1967) corrections for the dunes presence, while the blue squares marked as W are performed with the Wright and Parker (2004) correction. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula resistance formula with the different dunes correction. All the parameters used for these simulations are found in Appendix C in Table 5 and in Table 4.

flow parameters, as described by Equation 76.

Since other base flow parameters did not show meaningful trends, σ was then analysed as a function of the distance from the resonant condition, in Figure 19, which clearly shows a peculiar behaviour of the simulations. σ reaches a minimum (~ 3) around the resonant condition and it increases the farther away β is from β_R . While the values of σ around the resonant condition seem reasonable, its increase for super- and sub-resonant simulations does not fit with previous published data. To understand the cause of this behaviour the results were further analysed, highlighting the presence of small oscillations and a tendency of the ends of the planform to fold, particularly in the case of simulations further away from the resonant condition. To solve the former issue an additional filtering step was introduced, with the Savitzky–Golay filter, already implemented in the model, which reduced signif-

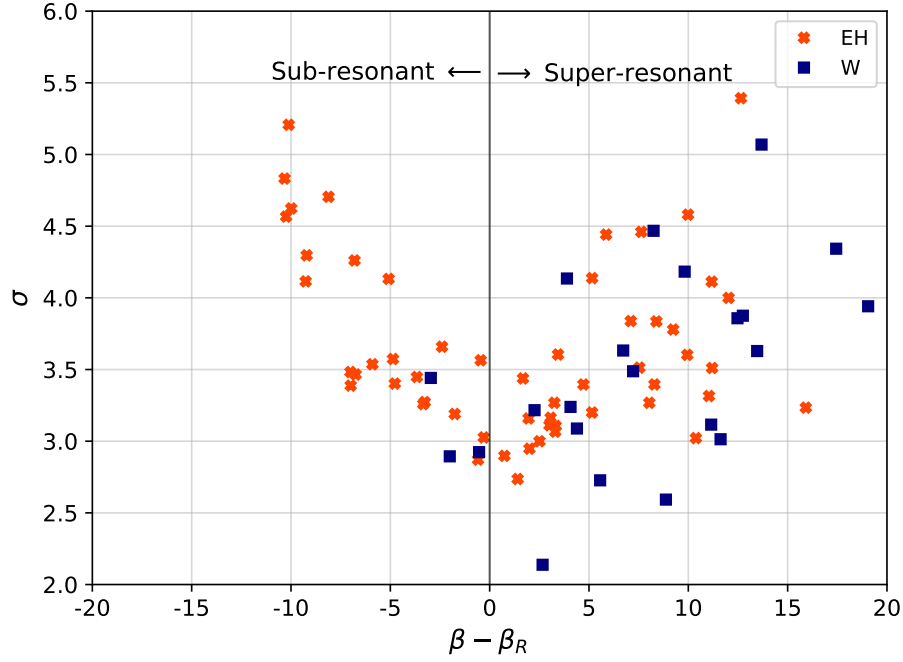


Figure 19 – Total sinuosity (σ) plotted against the distance from the resonant condition ($\beta - \beta_R$) for a set of simulations of sand bed rivers. Each entry is the average in time and between bend for the steady state of a given simulation. The simulations for this plot were performed with the Engelund and Hansen (1967) transport formula and resistance formula with the different dunes correction. The orange crosses marked as EH are simulations performed using the Engelund and Hansen (1967) correction for the dunes presence, while the blue squares marked as W are performed with the Wright and Parker (2004) correction. All the parameters used for these simulations are found in Appendix C in Table 4 and in Table 5.

icantly the total sinuosity. Moreover, to solve the problem occurring at the upstream and downstream margins, a few bends were removed at each end of the planimetry, avoiding the introduction of unrealistic shapes. The results shown in Figure 19 are however already processed with both of these steps and it did not affect the overall shape of the plot, albeit lowering its extremities. In an effort to find a more permanent solution to this issue, some further testing was performed with the different types of boundary conditions proposed in Lanzoni and Seminara (2006), but this did not show any significant improvement, so the removal of the incriminated bends was deemed more effective. These two techniques combined helped in reducing the total sinuosity of the bends, but is worth mentioning, however, that this correction did not affect the simulations close to the resonant condition, leaving σ for those simulations almost untouched. As mentioned earlier, comparisons with current

pre-existing works (e.g. Frascati and Lanzoni (2010)) showed also that the results of this PhD work seems to be overestimating σ , albeit most of the studies with these models did not show the total sinuosity. However, in the cases where it is possible to evaluate the position of the simulations in the space plotted in Figure 19, the simulations were rather close to the resonant condition and so their results fitted within the finding of this dissertation.

As mentioned for ψ , it is interesting to analyse the differences between the simulations performed with different dunes correction. In spite of having different base flow parameters, they clearly show a similar behaviour for all three morphometric properties, showing that is the distance from the resonant condition that has control over the meanders behaviour. For instance, a simulation with the same initial parameters ($\beta_{\text{in}} = 15$, $\tau_{*,\text{in}} = 2.5$, $d_{s,\text{in}} = 7.5 \cdot 10^{-5}$ and $R_{p,\text{in}} = 20$) has a sub-resonant steady state ($\beta - \beta_R \sim -4.8$), with an average total sinuosity of $\sigma \sim 3.6$ if the simulation is performed with the Engelund and Hansen (1967) correction. However, if the same simulation is performed with the Wright and Parker (2004) correction, the simulation is much closer to the resonant condition ($\beta - \beta_R \sim -0.5$) and has a total sinuosity $\sigma \sim 2.9$. Hence, the importance of the distance from the resonant condition is confirmed, as just looking at the other bankfull geometry parameters does not explain the behaviour of the simulations. However, this also highlights the importance of the complex choice of resistance and transport formula, as they have a significant impact on the results of a simulation, when comparing simulations with the same initial parameters or even the same steady state.

While the causes of this behaviour in σ were not further identified during this PhD work, the striking difference between the planimetries for near-resonant and far-from-resonant simulations was clearly visible when looking at the configuration of each simulation. In particular, near-resonant simulations displayed an overall less sinuous meander belt, which can be defined as the space which is occupied by the reach during its evolution, ultimately looking more streamlined. On the other hand, super- and sub-resonant simulations showed a more complex meander belt that moved more freely and further away from the initial

straight condition, showing a more complex planimetry.

On this note, gravel bed rivers simulations also showed the same behaviour, as it can be seen in Figure 20, supporting the results obtained for sand bed rivers.

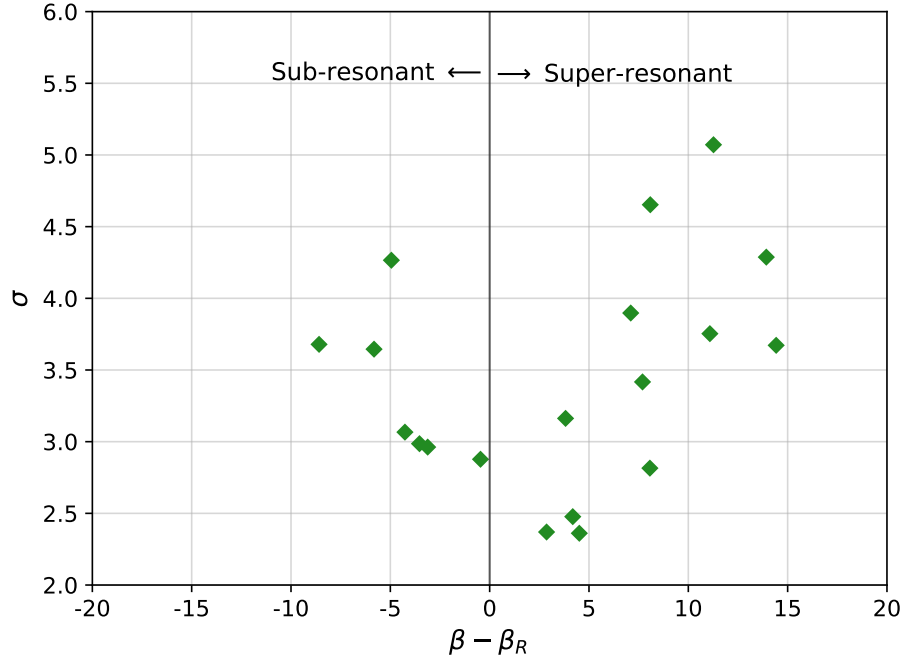


Figure 20 – Total sinuosity (σ) plotted against the distance from the resonant condition ($\beta - \beta_R$) for a set of simulations of gravel bed rivers. Each entry is the average in time and between bend for the steady state of a given simulation. The simulations for this plot were performed with the Parker (1990) transport formula and the Keulegan (1938) resistance formula. All the parameters used for these simulations are found in Appendix C in Table 3.

Concluding, the distance from the resonant condition appears to influence greatly the morphometric configuration of meandering rivers in the simulations. While this is not necessarily a surprising results, since the theoretical findings denote a difference in behaviour between the two regimes, it is still relevant to define those differences accurately. In particular, as it will be clear in section 3.2, this results allow for a quick and easy description of the response of meandering rivers to changes in their bankfull geometry, which is useful to understand the effects of external stressors on the meanders configuration. Moreover, since the difference between β and β_R is a complete descriptor for the steady state, the results denotes a clear link between the planimetric configuration and the bankfull geometry, not

only on the individual bends, but also on the entire structure of the planimetry.

3.1.3 Comparison with satellite data

To validate the model results satellite data are the best available option, but since their bankfull geometry is not readily available, the skewing angle was used as described in the previous section. As most of the rivers in the dataset are sand bed rivers the simulations chosen for the comparison were the ones performed with the Engelund and Hansen (1967) correction for the dunes presence, while for the satellite data only rivers in a temperate and tropical climate were selected, kindly provided by Federico Monegaglia and published in Bonanomi et al. (2024).

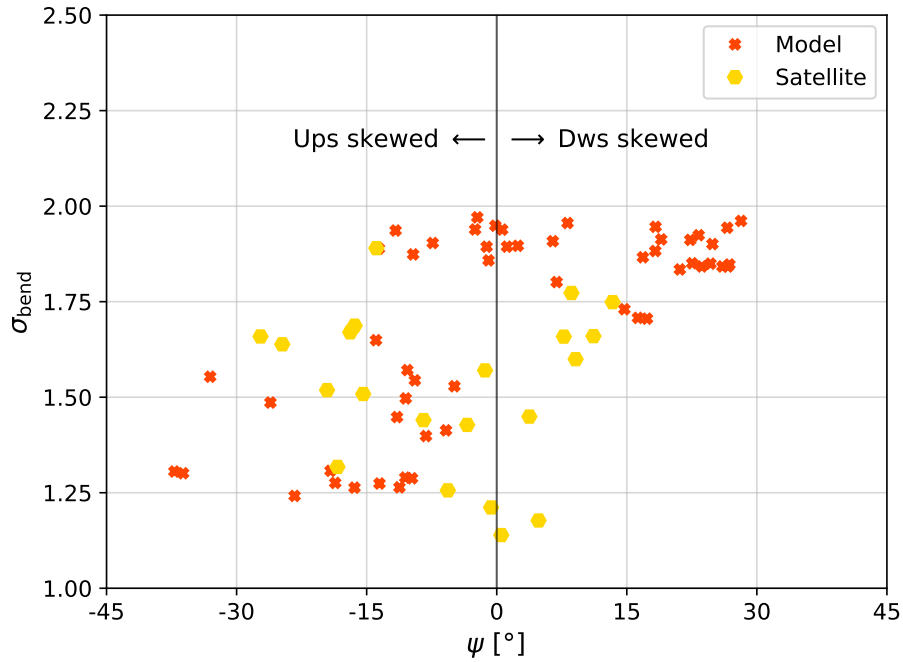


Figure 21 – Bend sinuosity (σ_{bend}) plotted against the bend skewing angle (ψ) for a set of simulations (orange Xs) and a set of rivers extracted from satellite data (yellow hexagons). ψ is positive if the bend is skewed downstream and negative if it is skewed upstream. Each entry is the average in time and between bend for the steady state of a given simulation or river. The simulations for this plot were performed for sand bed rivers with the Engelund and Hansen (1967) dunes correction and are reported in Appendix C in Table 5. The satellite data are the non-permafrost rivers described in Appendix D in Table 8.

In Figure 21 is plotted the bend sinuosity (σ_{bend}), with orange Xs for the simulations

results and yellow hexagons for the satellite data. While the range seems similar, which is important for the model accuracy, the pattern of σ_{bend} found in Figure 17 are not recognizable in the satellite data. However, this could actually be an effect of the inability of the model to represent the regime variability showed by single bends in real rivers. As per the Zolezzi, Luchi, and Tubino (2009) findings one would expect higher sinuosity in the sub-resonant regime bends, so for upstream skewed bends, as showed by Guo et al. (2019), because of the tendency of meandering bends of moving from the super- to sub-resonant regime while they elongate. However, the reader will remember from the previous section that the model is not able to reproduce it.

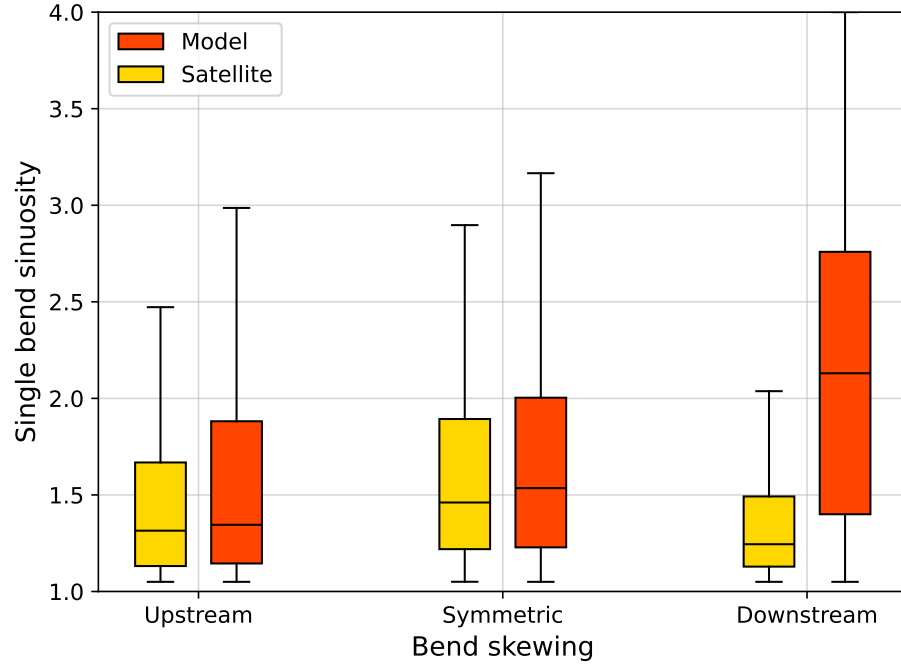


Figure 22 – Bend sinuosity (σ_{bend}) box plots compared for different classes of bend skewing angle (ψ) for a set of rivers extracted from satellite data (yellow) and a set of simulations (orange). The three classes corresponds respectively to ψ between -90° and -30° for upstream skewed bends, between -30° and 30° for symmetric bends and between 30° and 90° for downstream skewed bends. The black line in the box represents the distribution median, while the end of the box are the first and third quartile, calculated with the use of the *boxplot* function of the Python library *matplotlib*. The simulations for this plot were performed for sand bed rivers with the Engelund and Hansen (1967) dunes correction and are reported in Appendix C in Table 5. The satellite data are the non-permafrost rivers described in Appendix D in Table 8.

To confirm this thesis, in Figure 22 it is possible to compare the box plots for the σ

divided into three bend skewing angle (ψ) classes: upstream skewed, downstream skewed and symmetric. The results for the satellite data show that, albeit the higher σ_{bend} is reached in the symmetric bends, among the two remaining classes upstream skewed bend are more sinuous than their downstream skewed counterparts, which is in line with the behaviour described by Guo et al. (2019). On the other hand, the model results display higher σ_{bend} for downstream skewed bends followed by the symmetric ones.

To demonstrate however that the simulation results would hold when looking at a river that is entirely sub- or super-resonant, in Figure 23 are compared the box plots for the σ_{bend} divided into river regime classes for the model results and the Lagasse et al. (2004) database. While a direct comparison with the satellite results is not possible due to missing ψ for the bend of the Lagasse et al. (2004) database, using the bankfull geometry allows for a more precise comparison with the model results. As it can be seen in the plot, the behaviour of the Lagasse et al. (2004) data is similar to the model results, while the range of the model is much larger, probably due to the sheer number of simulated bends. These results appear to be in contrast with the findings retrieved from satellite data, but this discrepancy can be easily explained. The bends extracted from satellite data are automatically identified by means of detecting the inflection points as the zeros of the curvature distribution and then, following Guo et al. (2019), bends that have an amplitude lower than one width or are shorter than 4-times the width are discarded, but this still leaves plenty of low sinuosity bends in the distributions, including the young super-resonant bends that could then turn into sub-resonant bends (Zolezzi, Luchi, & Tubino, 2009). The Lagasse et al. (2004) database on the other hand contains bends that are hand-picked, generally leaving the younger low-sinuosity bends out of the analysis, thus showing super-resonant bends that did not switch regime and so their distribution are much closer to the model results. A similar consideration could be made by looking at the results proposed by Lopez Dubon et al. (2025) for remotely sensed data, where they imposed a minimum bend sinuosity of 1.5 obtaining a database where the considerations made for the Lagasse et al. (2004) database

holds. Indeed, they obtain higher sinuosity for the downstream skewed bends and lower sinuosity for upstream skewed bends as for the model results and the Lagasse et al. (2004) database.

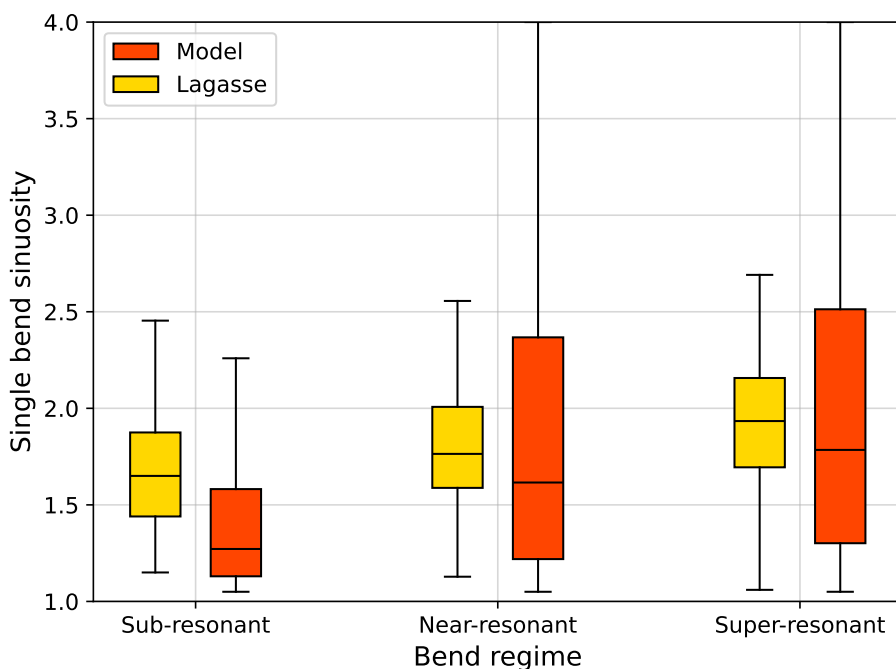


Figure 23 – Bend sinuosity (σ_{bend}) box plots compared for different classes of distance from the resonant condition for a set of bends from the Lagasse et al. (2004) database (yellow) and a set of simulations (orange). The three classes corresponds respectively to $\beta - \beta_R$ between -20 and -5 for sub-resonant conditions, between -5 and 5 for resonant conditions and between 5 and 20 for super-resonant conditions. The black line in the box represents the distribution median, while the end of the box are the first and third quartile, calculated with the use of the *boxplot* function of the Python library *matplotlib*. The simulations for this plot were performed for sand bed rivers with the Engelund and Hansen (1967) dunes correction and are reported in Appendix C in Table 5. The data from the Lagasse et al. (2004) database are all the sand bed rivers with a complete set of bankfull geometry parameters.

As shown before, the other relevant parameter that describes the planimetric configuration of meandering rivers is its total sinuosity (σ), which however is not as easy to extract from satellite data as the single bend metrics, such as σ_{bend} , because more often than not the length of the extracted reach depends on the satellite image boundaries, rather than on morphometric choices. Since this can affect the value of σ , it is not automatically guaranteed that the river is long enough to be compared with the model results.

To ensure that only suitable rivers are selected, various techniques are discussed. The most effective found during this PhD work consisted in searching for an asymptotic behaviour of σ when the length of the analysed reach is increased, meaning that σ would stay constant after a certain reach length, specific for each river. This analysis was performed dividing the planimetries into sub-reaches of varying length and looking at how σ would change increasing this length. For the simulations results, σ stabilized around a set value of sinuosity after a certain length and so the technique was deemed effective. For satellite data, however, not all the river showed the same asymptotic behaviour and for that reason only the planimetries that would reach a near-constant σ were considered.

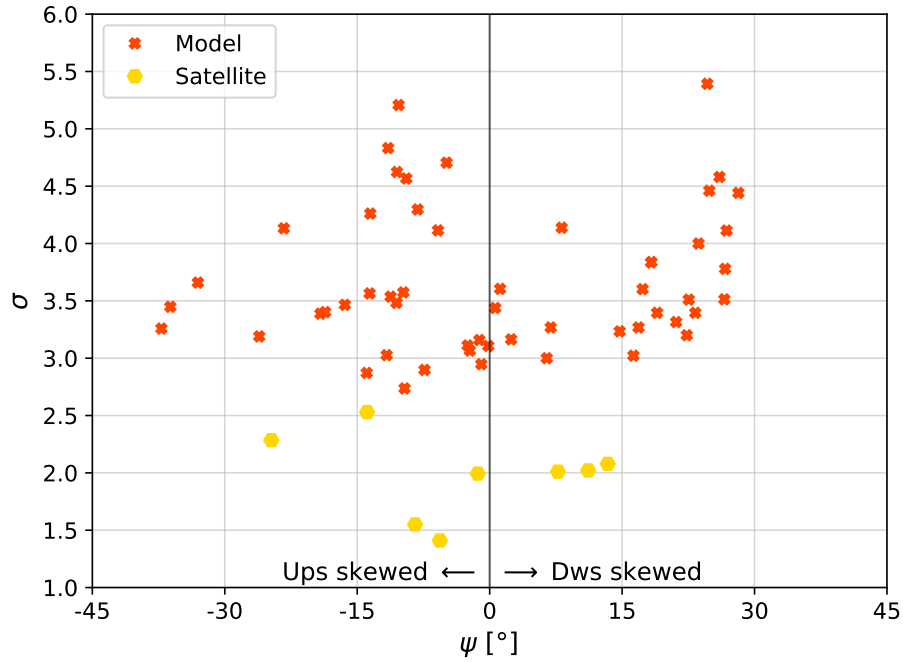


Figure 24 – Total sinuosity (σ) plotted against the bend skewing angle (ψ) for a set of simulations (orange Xs) and a set of rivers extracted from satellite data (yellow hexagons). ψ is positive if the bend is skewed downstream and negative if it is skewed upstream. Each entry is the average in time and between bend for the steady state of a given simulation or river. The simulations for this plot were performed for sand bed rivers with the Engelund and Hansen (1967) dunes correction and are reported in Appendix C in Table 5. The satellite data are the non-permafrost rivers described in Appendix D in Table 8.

In Figure 24 is shown the comparison between the satellite data and the model results. The plot display a small tendency of the data to reach a minimum close to the zero ψ , as

in the model. However, the striking result from this comparison is however the constantly lower σ of real rivers compared to the model output. This denotes another clear shortcoming of the model, albeit the cause here is not readily apparent compared to issues displayed by the single bend sinuosity.

Concluding, σ_{bend} values of the model results are in a comparable range with real rivers bends, while however not being representative of the bends that transitions between the two regimes. However, the current structure of the model is only able to represent rivers that are either fully sub- or super-resonant and a complete picture can only be obtained dividing the rivers in sub-reaches with different base flows, as it is done with the new local base flow update discussed in section 2.1.5.1. On the other hand, the model overestimates greatly σ compared to satellite data, which does not present a readily identifiable solution.

Among the various issues that could be responsible for this discrepancy, a few were discussed during this PhD study. As described earlier, changing the boundary conditions for the flow field solution was briefly tested, but it did not seem to have a significant effect in reducing σ . Some issue could arise from the flow field solution, especially for larger values of β , where the linear model is probably not that accurate in reproducing the bed topography. On top of that, the cutoff modelling could be improved, as mentioned in section 2.1.3.2, and a better implementation could help to reduce σ . On one hand, the addition of chute cutoffs will reduce the number of bends reaching a higher σ_{bend} , slowing overall the elongation process. As discussed earlier, how to model chute cutoffs is however still unclear and it will probably either require a more comprehensive description of the flow field and erosion process, adding the possibility of overflowing based on the bed topography, or a statistical approach that would introduce a set number of chute cutoff based on the timing and spacing found in nature. On the other hand, neck cutoff tend to generate a local increase in curvature that entails faster migration, but this is not always the case in real rivers. As showed in Richards and Konsoer (2020) and Richards et al. (2022), the complex interaction between the active channel and the abandoned bend can lead to a per-

sistent oxbow lake, de facto inhibiting the erosional ability of the river for long periods of time after the cutoff. Bogoni et al. (2017) tested variable erosion for the post-cutoff oxbow lakes finding lower bend sinuosities when the erodibility lowered after the cutoff, but under the assumption of constant non-zero erodibility, once the cutoff had happened. In the case presented in this PhD work, time changing erodibility would be more appropriate, because it could better represent the slow process of oxbow lake infilling (Gautier et al., 2007) and ultimately of the ability of the river in eroding the floodplain in that area.

Moreover, as shown by Bogoni et al. (2017) and Güneralp and Rhoads (2011), the floodplain heterogeneity can have a non-trivial effect on meandering rivers dynamics, possibly leading to a sinuosity reduction. For instance less erodible areas of the floodplain could result in a more streamlined meander belt and, as discussed earlier, this is a characteristic of near-resonant simulations with homogeneous erodibility and lower σ .

Finally, the field survey of the Sabine River pointed towards a new direction, due to the presence of recirculation cells along the outer bank of the bends. As mentioned by Blanckaert (2011), these cells could protect the outer bank from the erosion, ultimately reducing the elongation, which seems to be confirmed by satellite observations on the river. The linear solution is clearly not able to reproduce that phenomena, but a few parametrizations could be employed to mimic the effect of these recirculation cells. Since the database described in section 2.3.2 allows for a complete description of this and other phenomena happening in high curvature bends, section 3.1.4 will be dedicated to their analysis and the possible implications for the model.

While none of these proposals alone are probably resolute, a combination of these effects could help improve the model performance when compared to real rivers planimetries. Thus, even if this is not the scope of this PhD work, discussing the future of the research of the long term evolution of meandering rivers can be inspiring for future analysis.

3.1.4 High curvature bends and recirculation cells

As mentioned before, a few peculiar phenomena were observed during the field survey of the Sabine River, especially in high curvature bends.

3.1.4.1 Recirculation cells

In particular, the presence of recirculation zones in the outer bank of said high curvature bends stood out for their possible model implications. The longitudinal velocity (U) are

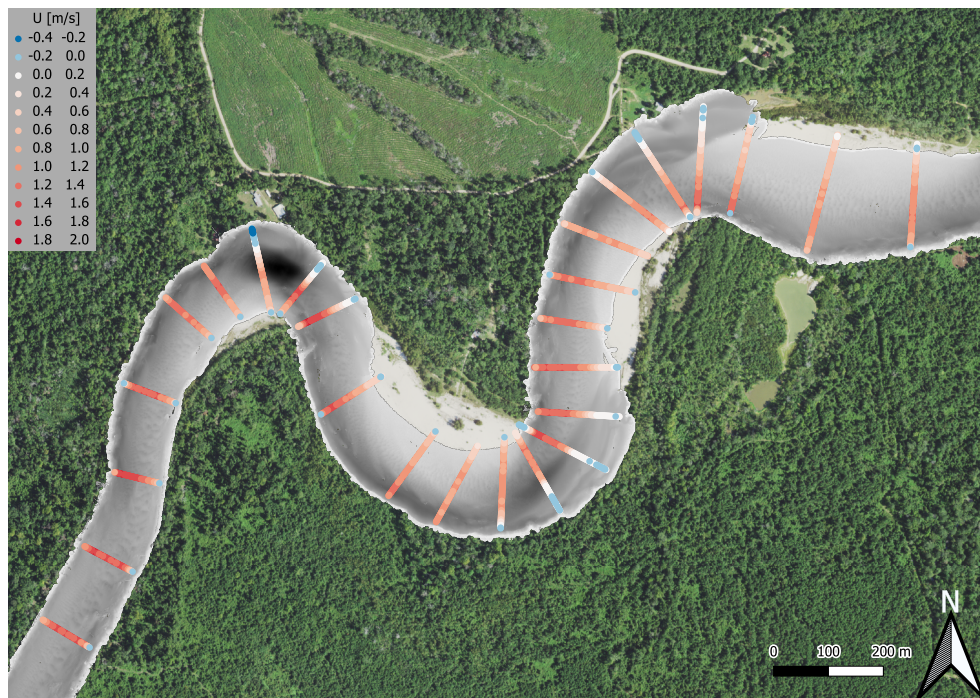
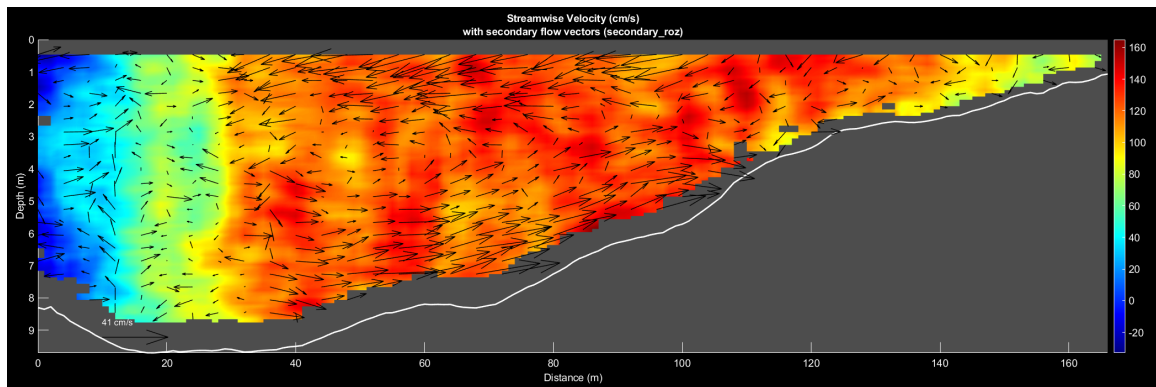


Figure 25 – Map of the higher curvature bends of the Sabine River with the vertically averaged longitudinal velocity (U) distribution. The darker red shade represents higher velocities, the whitish points near-zero velocities and the blue ones negative velocities. The recirculation zones are visible in the outer bank of the bends, generally just before the bend apex and they extend along the longitudinal direction for a few river widths. The background map is the NAIP orthophoto from 2022 ©USDA.

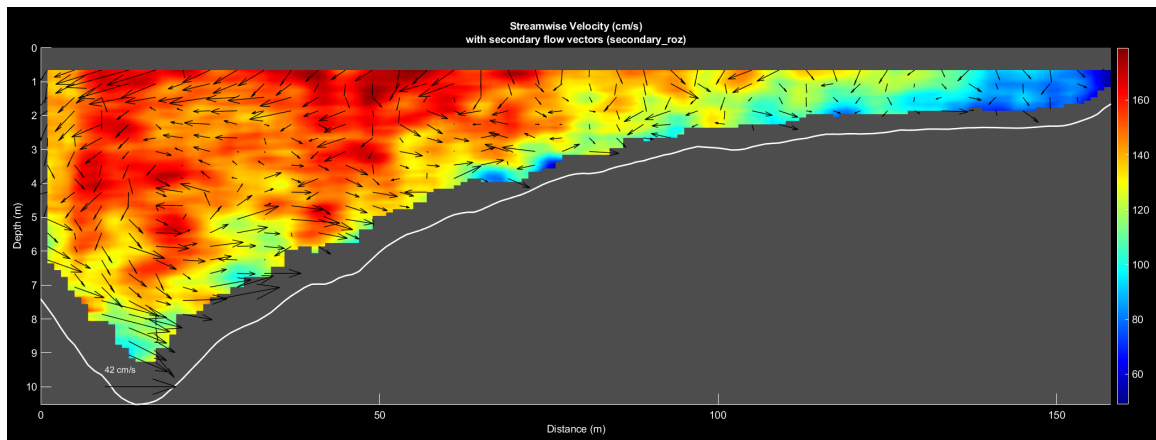
reported in Figure 25, where each point is the vertical average over the 1 m bins measured by the ADCP. Darker red shade represents higher values of U , while whitish or blue points indicate respectively near-zero and negative values of U . The recirculation zones are clearly visible in the outer bank of the bends, generally just before the bend apex and they extend

along the longitudinal direction for a few river widths.

These recirculation cells are not new discoveries and they were described at length with laboratory experiments (Blanckaert, 2010, 2011; Blanckaert & Graf, 2004), non-linear modelling Ottevanger et al. (2013), or a combination of the previous (Blanckaert & De Vriend, 2004; Ottevanger et al., 2012), with some field data collection (Deng et al., 2021) too. The various work focused on the identification of the complex flow field structure of high curvature bends in meandering rivers. In particular, as it can be seen in one of the



(a) XS 52



(b) XS 78

Figure 26 – Two cross-sections (XSs) measured in the Sabine River with the ADCP showing the longitudinal velocity (U) with the colour map and the secondary circulation with the vectors. In (a) is reported a XS with a recirculation zone in the outer bank (left), with the two classic smaller cells of secondary circulations and low to negative velocities. In (b) is reported a XS with no recirculation zone, with a single larger secondary circulation cell in the deeper part on the outer bank (left) of the XS. Both plots were generated with the VMT software (Parsons et al., 2013) and for that reason the colour map legend values are expressed in cm/s.

XSs in Figure 26a measured in the Sabine River, the outer bank of high curvature bends

presents a low velocity zone with two secondary cells circulations, one closer to the water surface and one closer to the bottom. Regular XSs on the other hand, like the one reported Figure 26b, tend to have the highest velocity closer to the outer bank and a single larger secondary circulation cell (Rozovskii, 1957).

To identify the recirculation cells, an automatic process was put in place to detect them based on the ADCP measurements. Firstly, a velocity threshold was set, below which an area would be considered a recirculation zone. Moreover, it was also imposed that the zone should extend from the river bank for at least three 1 m bins (as generated by the ADCP measurements) to avoid false detection of low speed areas that were not related to this phenomenon. The velocity threshold was set at 0.2 m/s after some careful consideration on the flow field data. In particular, looking at various XSs, recirculation zones occupy the area between the outer bank and the thalweg, with velocities below 0.2 m/s. Figure 25 paint the same picture, since the outer banks velocities in blue and white are respectively negative or between 0 m/s and 0.2 m/s, and it is possible to see that they are found between the bank and the thalweg, which is indicated by a darker grey tone in the bathymetry. One could wonder why not to set the threshold at 0 m/s, but this would underestimate considerably their width and the chosen threshold seems much more appropriate when looking at the XSs.

This approach allows for an analysis of the width of the recirculation zones as shown in Figure 27, where is displayed the centreline curvature distribution on the bottom part of the plot and the width of the zones in the left and right banks, on the top part of the plot. Blanckaert (2011) describes how these recirculation zones appear in high curvature bends, defining them as bends with curvature ($\mathcal{C}$) higher than 0.25, which is consistent with the reported observation. Indeed, all the bends that display recirculation zones have a $\mathcal{C}$ higher than 0.5 and all the other bends have $\mathcal{C}$ lower than 0.2. Blanckaert (2011) also reports that the width of these zones generally scales with the river depth, but they tend to become larger with higher bank roughness. This seems to be the case in the Sabine River, where

the banks were mostly vegetated, that presents rather wide recirculation zones compared to the depth, as shown in Figure 27. Beyond purely scientific curiosity, recirculation zones

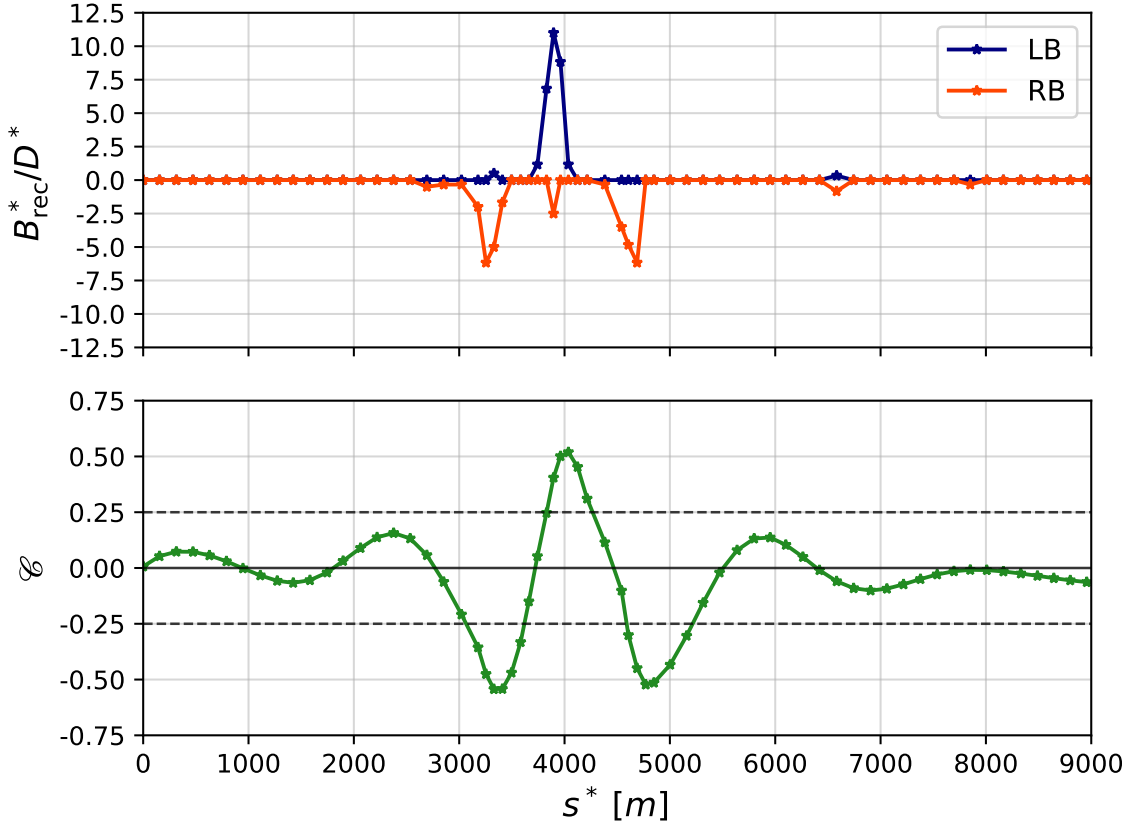


Figure 27 – The plot on top represents the width of the recirculation zones (B_{rec}^*) along the longitudinal coordinate in the curvilinear Cartesian reference system (s), normalized with the averaged depth (D) of the river, while the plot on the bottom is the curvature ($\mathcal{C}$) distribution of the centreline. The recirculation zones are distinguished between left (LB in blue) and right (RB in orange) bank and they were defined as the contiguous zones with velocities lower than 0.2 m/s extending from the banks at least for three 1 m bins. In the $\mathcal{C}$ plot are highlighted with dashed lines the 0.25 limit proposed by Blanckaert (2011) to identify high curvature bends. The background map is the NAIP orthophoto from 2022 ©USDA.

can be helpful in the framework of the MCMM, because they should protect the river bank from erosion as theorized by Blanckaert (2011), slowing down the migration of the river. However, this was only based on considerations on the flow field data, with little evidence from migration or erosion data backing up the study hypothesis.

3.1.4.2 Migration of the Sabine River

In the case of the Sabine River, the analysis performed with PyRIS on 40 years of Landsat data, in Figure 28, shows that the river is only migrating downstream, with almost no elongation or migration orthogonally to the flow direction. This is consistent with the position of the recirculation zones in Figure 25 and it aligns Blanckaert (2011) hypothesis.

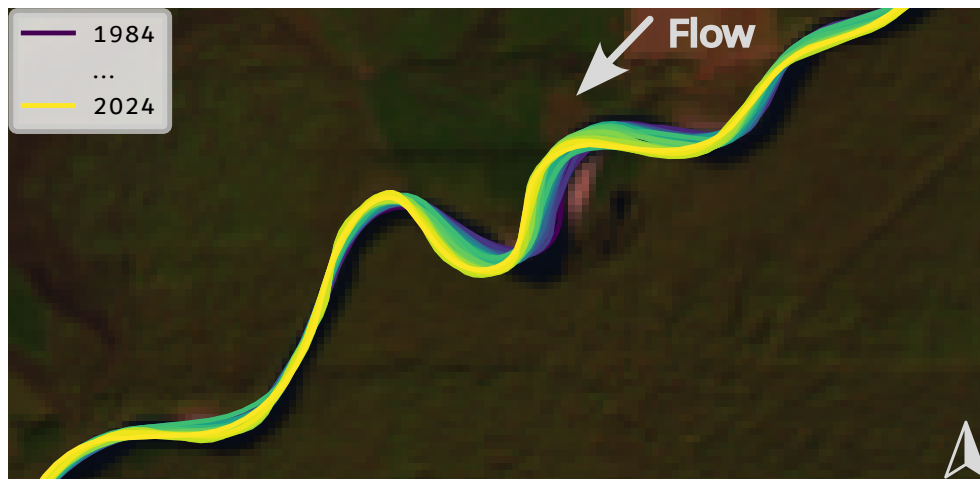


Figure 28 – Migration of the Sabine River over 40 years from 1984 (purple) to 2024 (yellow), evaluated with Landsat data analysed with PyRIS. The river is only migrating downstream with little bend elongation or migration orthogonally to the flow direction, as the recirculation zones observed in Figure 25 suggest. The background is the combination from the Red, Green and Blue bands of the Landsat 5 image collected on 30th November 1984.

3.1.4.3 Modelling implications for the recirculation cells

Since the evolution shown in Figure 28 keeps the sinuosity increase to a minimum, this becomes relevant for the MCMM model to solve the overestimation of σ showed in section 3.1.3. The linear solution is not really able to represent this outer banks cells, leading to higher velocities close to the river banks as it is apparent from Figure 29, where are reported the longitudinal velocity (U) calculated with the ZS solution for the Sabine River. While the maximum velocity is still found downstream the bend apex, as it should be with the sub-resonant regime of the river, the velocities are still high along the outer bank

of the entire bend. Since bank erosion in the model is calculated using the difference of the outer and inner bank velocities (Equation 7) the bends would not just migrate downstream with the flow field shown in Figure 29. Since the maximum velocity is close the apex in each of them, they will also elongate, ultimately leading to a much different planimetry compared to the real Sabine River.

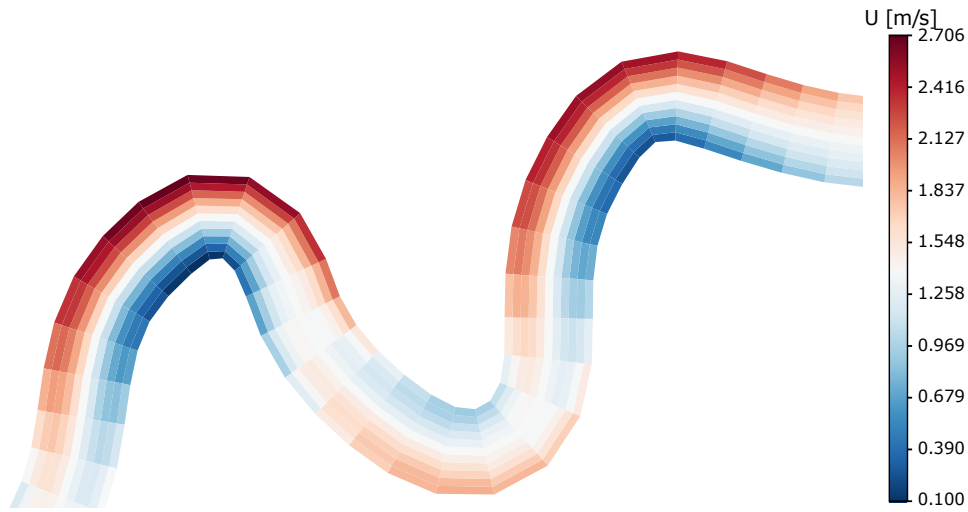


Figure 29 – Longitudinal velocity (U) distribution for the Sabine River calculated with the ZS solution. The higher red shade represent the highest velocities, while the blue one are the lowest. It is readily apparent that the highest velocities are reached close to the apex and there are no recirculation zones.

Using non-linear solutions would allow for a comprehensive description of these cells (Blanckaert & De Vriend, 2004; Ottevanger et al., 2013), but it would also add complexity to the model, leading to a less suitable approach for long term simulations. However, it is still possible to encompass this phenomenon using a curvature-dependent limiter for the erosion, with a multiplying coefficient of the erodibility E . With this coefficient going from one at low curvatures, to zero for curvatures higher than a curvature threshold this could help in solving the high sinuosity issues. Even so, this still requires more research and fine-tuning to be fully operational in the model. For instance, while it is true that they appear only in high curvature bends, they extend longer than just the areas with curvature above the threshold, implying a more complex control of the curvature on the migration. Moreover,

the function to set the coefficient, has to be tuned to avoid artefacts and instability in the migration where it goes to 0. Despite that, the introduction of the recirculation zones is a first step in the improvement of the linear model, and a simple parametrization of their effects could help without having to resort to a complete different flow field solution and approach.

3.1.4.4 Scour holes

Other than the recirculation zones, one bend of the Sabine River displayed also another interesting effect, which seems also to be connected with high curvature. While most of the XSs observed in the more sinuous reach displayed a maximum depth at the thalweg of around 12 m, with an average depth across the entire reach of 6 m, in the last high curvature bend was found an almost circular scour hole with the maximum depth around 20 m, as shown in Figure 30. This is a recurrent occurrence in high curvature bends displayed

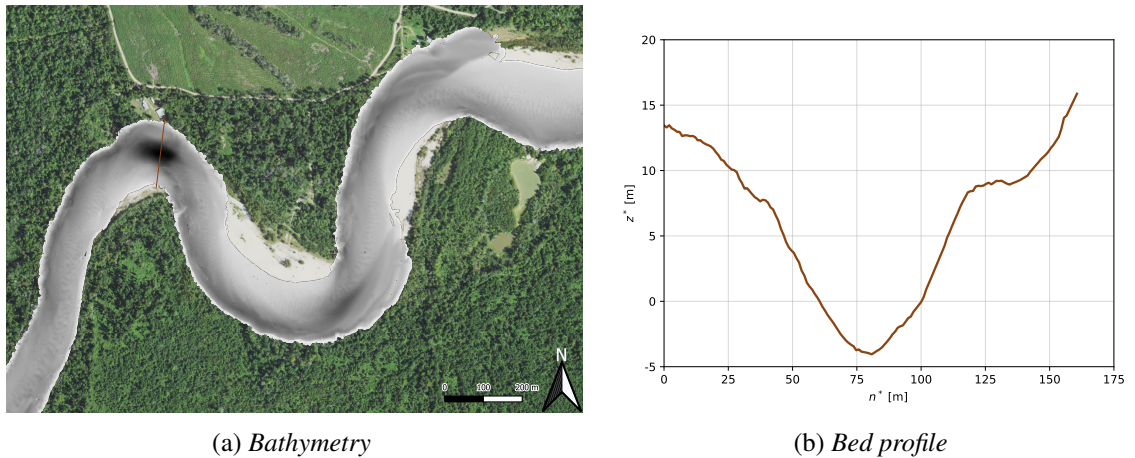


Figure 30 – (a) Bathymetry and (b) bed profile of the circular hole found in the last bend of the high curvature bend train in the Sabine River. The brown line in the map represents the XS where the profile was extracted. The hole is almost 20 m deep and is similar to the scour holes measured in the Mahakam River (Vermeulen et al., 2014). The background map is the NAIP orthophoto from 2022 ©USDA.

for instance in the Mahakam River in Indonesia (Vermeulen et al., 2014). Vermeulen et al. (2015) outlined the complex three-dimensional flow structure leading to the presence of such holes, with a shape and position that recalls what was measured in the Sabine

River. However, in the Mahakam River this scour holes are much more common and deep, probably due to the particular morphology of the river, which alternates long straighter reaches and sharp bends, in a peculiar configuration.

3.2 Effects of sediment supply alterations on the bankfull geometry

Using the relationship between the planimetric configuration and the bankfull geometry described in section 3.1.2, it becomes possible to evaluate how the bankfull geometry changes under external forcing and then, using the aforementioned relationship, connect it to the corresponding evolution of the planimetric configuration. After an interesting presentation by Parker and Török (2023), the focus was posed to the effects of an increase in sediment supply due to land use changes, however, similar consideration could be made for decreasing sediment supply or changing liquid discharge.

Imposing a sediment discharge increase equal to

$$Q_s = \alpha Q_{s0} \quad (96)$$

and with the hypothesis of constant liquid discharge and uniform flow, it is possible to evaluate the new equilibrium bankfull geometry conditions using just the resistance and transport formulas, and an appropriate width evolution model. However, for the latter ingredient, the use of regime formulas did not give meaningful results, and it is not easy to extract an equilibrium condition without knowledge of the timescale of the width evolution, when using a model such as the one developed by Monegaglia et al. (2019) or by Viparelli and Eke (2021). Thus, the width has also been considered constant in the calculations, but a future development of this simple tool could include an appropriate width evolution model.

The calculation process becomes rather simple then. Starting from Equation 96, it is possible to evaluate the change in Shields parameter (τ_*) with the appropriate transport formula. Under the hypothesis of uniform flow, τ_* can be written as described in Equation 24

and so it is possible to evaluate the changes compared to the initial condition as

$$\frac{DS}{D_0S_0} = \frac{\tau_*}{\tau_{*0}}. \quad (97)$$

Using Equation 94, Equation 95 and Equation 97 with an appropriate resistance formula, it is possible to determine also the value of D and S for each α value and from there the bankfull geometry parameters.

As described in section 2.1.4.2, gravel and sand bed rivers generally do not share the same resistance and transport formulas, so the results are presented separately for the two types of rivers. As a general note, to simplify the use of the inverse function of the resistance formulas, all the logarithmic resistance formulas have been transformed into power-law formulas, as described in Equation 28.

3.2.1 Gravel bed rivers

For gravel bed rivers, the Keulegan (1938) resistance formula was used together with the Meyer-Peter and Müller (1948) transport formula. The resulting formulas for a variable α read

$$\frac{\tau_*}{\tau_{*0}} = \alpha^{\frac{2}{3}} \left(1 - \frac{\tau_{*cr}}{\tau_{*0}} \right) + \frac{\tau_{*cr}}{\tau_{*0}}, \quad (98)$$

$$\frac{\beta}{\beta_0} = \frac{d_s}{d_{s0}} = \frac{\tau_*}{\tau_{*0}}^{\frac{1}{2(m+1)}}, \quad (99)$$

with the critical value of the Shields parameter (τ_{*cr}) and with the exponent of the power law chosen as $m = 0.175$, as estimated with an empirical fit of the Keulegan (1938) resistance formula.

In Figure 31 are presented the results of the analysis in terms of distance from the resonant condition as a function of τ_* . The choice of using τ_* instead of the transport capacity was made to display all the parameters of the bankfull geometry in a single plot.

Each curve represents the series of subsequent equilibrium states reached by the bankfull geometry parameters for the increasing sediment supply, starting from the initial conditions marked by a black X. As it can be seen in the plot, the increase in sediment supply leads to a decrease in value of the difference between β and β_R . From the results discussed in section 3.1.2 it is possible to infer the change in total sinuosity caused by this alteration of the bankfull geometry, which will depend on the regime of the river. For instance, a near-

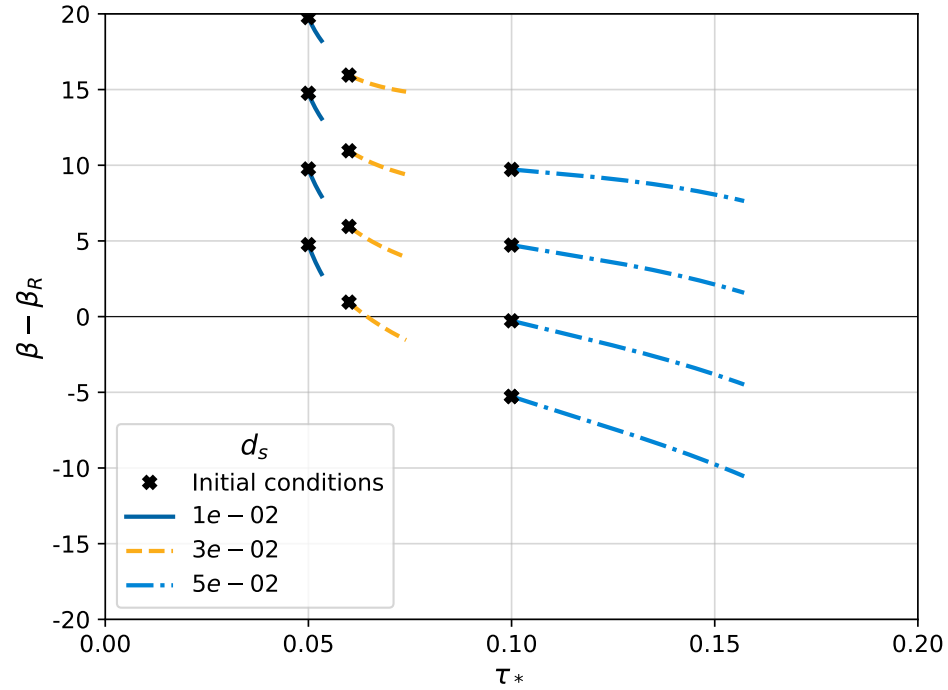


Figure 31 – Distance from the resonant condition changes when increasing the sediment discharge up to three times plotted as a function of the Shields parameter (τ_*) in gravel bed rivers. The calculations are performed with the Keulegan (1938) transport formula and the Meyer-Peter and Müller (1948) resistance formula, rewritten as a power law. Each curve represent the series of subsequent equilibrium states reached by the bankfull geometry parameters when increasing the sediment supply. The starting point of each curve, marked by a black X, has different β , τ_* and d_s . The initial value of the latter parameter is shown as colour of the curve.

resonant or sub-resonant river will tend to increase its total sinuosity since it will move further away from the resonant condition, while a super-resonant one will tend to get closer to the resonant condition, thus decreasing its total sinuosity.

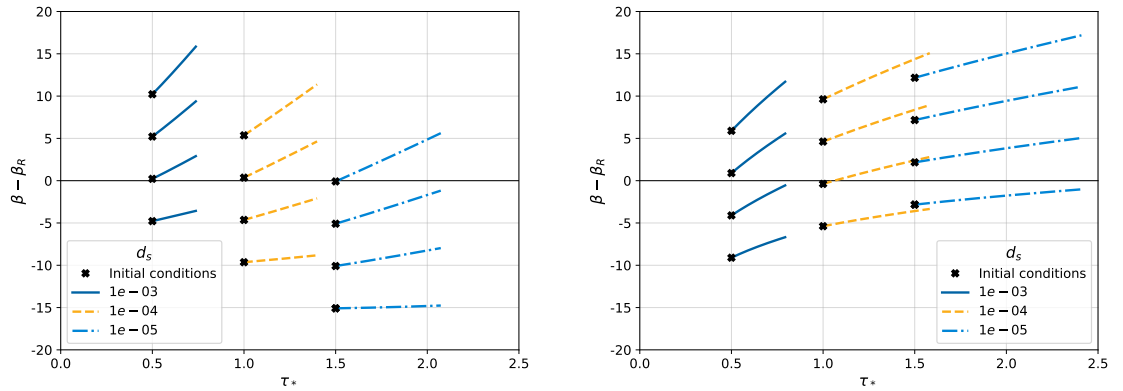
3.2.2 Sand bed rivers

For sand bed rivers, the Engelund and Hansen (1967) transport formula was used together with the Engelund and Hansen (1967) resistance formula, distinguishing between the dunes corrections developed in the original work and the ones proposed by Wright and Parker (2004). The resulting formulas read

$$\frac{\tau_*}{\tau_{*0}} = \alpha^{\frac{2m}{3(3-m)} + \frac{2}{3}} \left(\frac{\tau'_*}{\tau'_{*0}} \right)^{\frac{2m+1}{2(m-3)}}, \quad (100)$$

$$\frac{\beta}{\beta_0} = \frac{d_s}{d_{s0}} = \alpha^{\frac{2m}{m-3}} \left(\frac{\tau'_*}{\tau'_{*0}} \right)^{\frac{3(2m+1)}{2(m-3)}}, \quad (101)$$

with the same exponent m as the one presented for gravel bed rivers. Since τ'_* depends on the bankfull geometry parameters, it is impossible to obtain an analytical expression as for the gravel bed rivers, but it is quite easy to solve it numerically. In Figure 32 are presented



(a) Engelund and Hansen (1967)

(b) Wright and Parker (2004)

Figure 32 – Distance from the resonant condition changes when increasing the sediment discharge up to three times plotted as a function of the Shields parameter (τ_*) in sand bed rivers. The calculations are performed with the Meyer-Peter and Müller (1948) transport formula and the Engelund and Hansen (1967) resistance formula, rewritten as a power law, with the (a) Engelund and Hansen (1967) and (b) Wright and Parker (2004) dunes correction. Each curve represent the series of subsequent equilibrium states reached by the bankfull geometry parameters when increasing the sediment supply. The starting point of each curve, marked by a black X, has different β , τ_* and d_s . The initial value of the latter parameter is shown as colour of the curve.

the results in the same way they were presented for the gravel bed case, distinguishing

between the two dunes corrections for the resistance formula. As showed by the curves, while both cases have a tendency to increase the difference between β and β_R , they have different curve convexity and while the change in distance from the resonant condition is similar, the results calculated with the Wright and Parker (2004) correction display a higher increase in τ_* , particularly at higher values of the same parameter. Regardless the differences shown by the two formulas, sand bed rivers behave in the opposite way compared to gravel bed rivers and so, near-resonant or super-resonant rivers will tend to increase their total sinuosity, since they become more super-resonant, while sub-resonant rivers will tend to get closer to the resonant condition, decreasing their total sinuosity.

3.2.3 Discussion

While these results are still qualitative and with significant constraints due to the hypothesis imposed, they still offer a quick way to interpret the effects of changing boundary conditions on the planimetry of meandering rivers. A few simulations with the MCM model were performed to try and visualize the effects show in this section, but the relatively small changes induced by the increase in sediment supply did not allow for a definitive answer, since the oscillations in the simulations tends to mask the effects of the sediment supply increase. Even though it is not clear the mechanism of this change in sinuosity, the differences showed in the simulations were in the complexity of the planimetric configuration and, although this is not yet evident in the simulations performed during this PhD work, it is expected that simulations getting closer to the resonant condition will ultimately streamline their meander belt and vice versa. One could argue that further increasing the sediment supply would lead to a more evident change, but, since the width and the liquid discharge are kept constant, it would probably be even more unrealistic. However, this simple model still helps to delineate the behaviour of meandering rivers, and in particular the change of regime, when the sediment supply is altered. For instance, this could happen when mining activities in the floodplain increased the sediment production, as in the

case proposed by Parker and Török (2023) on the Fly River, or it could be also caused by denudation of large portions of floodplain due to deforestation, which would increase the sediment availability without changing the hydrological regime. Moreover, glacier retreat due to climate change is also increasing the sediment availability, which could also increase the solid transport of rivers, particularly in alpine regions. On the other hand, damming or sediment mining in the river could actually reduce its sediment yield, without affecting the hydrology. With the aforementioned tool, one could infer the long term tendency of the river under the new condition and ultimately understand the long term trajectory of an impacted river.

3.3 Effects of local changes of transport capacity on the bankfull geometry

3.3.1 One-dimensional morphodynamic influence on meander bend evolution

The results presented in the previous section allow for a qualitative understanding of the effects of changing bankfull geometry on meandering rivers. However, like it was described in section 2.1.5, a more comprehensive parameter update added directly to the model would be necessary to be able to represent the transition to a new equilibrium state. Being able to consider the connection between slope, sediment supply and transport capacity and in general the one-dimensional morphodynamic influence introduced with the MT approach, allows for a better understanding of the river local evolution. Moreover, treating each bend or bend group separately leads to a correct representation of the bends transitioning between the two regimes, instead of having a single base flow for the entire river, solving one of the main issue found in the MCMM model.

For that reason, as mentioned in section 2.1.5.1, the MT approach was used in conjunction with the periodic solution applied to each bend individually and under the hypothesis of constant width. The choice of using the periodic solution was made to simplify the complexity introduced by the use of the multi-bend base flow approach and, in particular, to avoid the introduction of boundary conditions between each bend. While boundary con-

ditions do not affect the results in the long continuous reaches of the original model, since their effects decay in a few bends (Zolezzi & Seminara, 2001), when the reach consists of just a single bend, they become much more relevant. The choice of using the periodic solution allows for focussing only on the one-dimensional morphodynamic influence and to understand its effects on the bankfull geometry of each bend. Moreover, the MT approach describes the interaction between the slope variability and the sediment supply, the hypothesis of constant width just facilitates the analysis, without losing focus of the ultimate goal. Lastly, it is necessary to understand how to treat the cutoff occurrence. While this would not be a problem for the ZS solution, the distribution of θ is not describable any more after a cutoff with the periodic solution. For that reason, a few options were considered to treat the cutoff occurrence. One could ask if this is really necessary in a simplified model and the first option would be to simply end the simulation when the cutoff occurs. However, this limits greatly the duration of the simulation and disregards the cutoff effects on the neighbouring bends, and, ultimately, it would have been too restrictive to understand properly the effects of the one-dimensional morphodynamic influence. It clearly arises the need to take into account the increase in slope generated by the local shortening of the channel caused by a cutoff, since the elevation difference between the two points remains the same, but the path is greatly shortened. With the flow field solution for an arbitrary distribution of curvature one would just leave the new bend generated by the cutoff, as described in section 2.1.6, and the slope could be easily evaluated knowing the length of said bend and the elevation drop left by the cutoff. However, this is not possible with the periodic solution unless one arbitrarily decides the shape and length of the new bend, without a real connection with the cutoff process, which did not seem a meaningful approach. Therefore, it was decided to spread the elevation drop that is generated as a consequence of the cutoff between the upstream and downstream bends, increasing their slope, without adding any additional bends. Since the slope adaptation after a bend cutoff in a natural setting is generally not instantaneous, the time frame of this slope change was discussed,

to better mimic what would happen with the shorter bend left behind by a cutoff, but the definition of the timescale and of the parametrization of this evolution was not trivial. In the end then it was decided to simply increase the slope of the two neighbouring bends as

$$S_{\text{new}} = S + \frac{1}{2} \frac{S_{\text{cutoff}} L_{\text{cutoff}}}{L}, \quad (102)$$

when the cutoff occurred. The new slope S_{new} is calculated as the previous slope of the bend S plus the increase in slope due to the cutoff, which is equal to the slope of the removed bend S_{cutoff} multiplied by its length L_{cutoff} and divided by the length L of the bend where the slope is added. Equation 102 can be written directly with the normalized variables, since they are all scaled with the same zero-state parameters. While this is far from a perfect solution and, as it will be clear later in this section, generates a discontinuity in the bankfull geometry, it still allows encompassing the effects of the cutoff of one bend on the others and, since the cutoff is a discontinuity, this approach is probably not that far off reality.

To evaluate the effects of the MT approach on the bankfull geometry two different cases were modelled at different R_T values, to understand how the different evolutive timescales would affect the results. In both cases the initial bankfull geometry was the same for all bends and the R_T was the same for all bends. Moreover, the initial sediment supply for the upstream bend was kept constant for the entire simulation, under the hypothesis of a non-changing supply from the upstream basin.

The first group of simulations was performed on two identical bends, which in the original periodic model or with the ZS solution will have an identical evolution till they both reach the cutoff at the same instant.

The picture changes however if the base flow is updated for each bend independently, as it can be clearly seen in Figure 33, where are plotted the normalized length (L above) and slope (S bottom) for three simulations performed with different values of R_T .

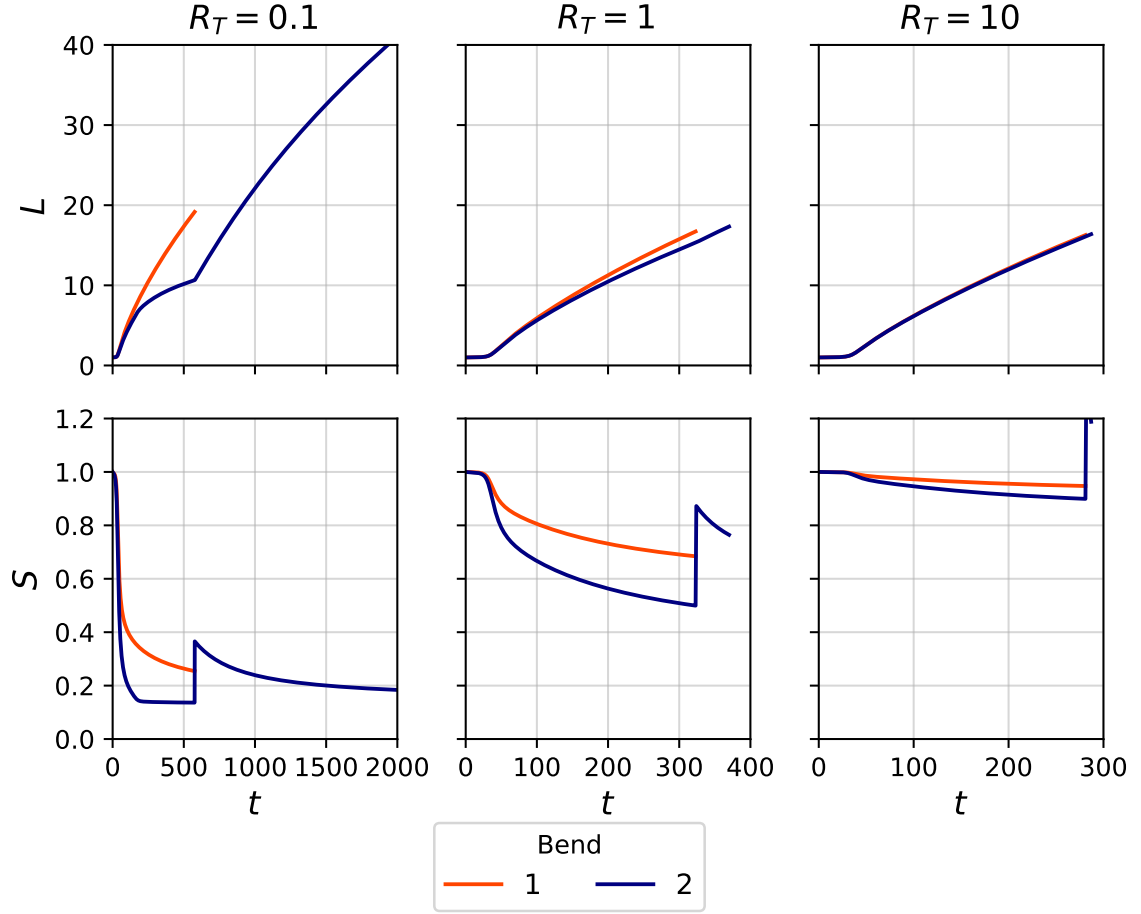


Figure 33 – Comparison of the evolution in time of two bends with the same initial condition ($\lambda = 0.1$ and $\theta_1 = 0.05$). The simulation started with initial parameters $\beta = 15$, $\tau_* = 0.2$, $d_s = 0.01$ and $R_p = 1000$, with the Keulegan (1938) resistance formula and the Meyer-Peter and Müller (1948) transport formula. On the top row are plotted the different values of intrinsic length of the channel axis (L) for the bends, normalized with the average value for the initial condition, while on the bottom row the river bed slope (S) is shown, normalized with its initial value. Each column has a different ratio between the planimetric and bed evolution timescales (R_T) value ranging from 0.1 to 10.

For high R_T s (10^1) the difference between the two bends is minimal, both in terms of L and S , albeit still being visible. On the other hand, for lower values of R_T (10^0), the difference is much more evident, with the sediment transport of the downstream bend being almost half of the one of the first bend and this is even more apparent with even lower R_T s (10^{-1}). This is caused by the elongation of the upstream bend whose slope decreases. Consequently, its transport capacity reduces, which provides the sediment supply for the

downstream bend. In this second bend the slope is decreasing even more since its sediment supply is reducing, but the bend is also elongating. While this happens in all the simulations, the effect is far more important for low R_T values, which imply a lower ability of the river bed to adapt to new planimetric configurations. The elongation shows also some differences, since the flow field is changing with the bankfull geometry, particularly for lower values of R_T . This asymmetry in the flow field leads to a different planimetric evolution between the two bends, which the original model is not able to represent.

Since the bend migration is described with the velocities, as shown by Equation 7, the difference in evolution does not depend on the sediment supply imbalance of a bend. However, the migration rate of meandering rivers has been linked to the sediment transport and supply (Constantine et al., 2014) and, if the migration was calculated with an erosion law based on the transport capacity, the difference in the evolution of the two bends could be also affected by the upstream sediment supply. As it can be seen by the S plot the cutoff works as a reset of the slope, but it also changes the evolution of the remaining bend, speeding it up in this case, since the bankfull geometry switches abruptly.

This first set of simulations helped in the understanding of the behaviour of the new model compared to the classic periodic solution, but it is not completely representative of the effects of the one-dimensional morphodynamic influence. The second set focused on bends at extremely different evolutionary stage to understand the effects of the evolution of a more mature bend and of the cutoff occurrence. In particular, this set of simulations contained a more elongated bend, in between four bend starting from a quasi-straight condition. In Figure 34 is reported the plot of L and S over time for the second set of simulations.

Starting from L , the evolution is quite different among the three R_T values. For $R_T = 10^1$ the central bend (3) reaches the cutoff before the other 4 start to elongate and when they do start to elongate it happens almost at the same time for every bend. For $R_T = 10^0$ the central bend (3) also reaches the cutoff before the other start elongating, but then the first two bend start before the last two bends. On the other hand, for $R_T = 10^{-1}$ the

downstream bends (4-5) start elongating before the cutoff occurs in the central bend (3), while the first two (1-2) have not even started evolving by the end of the simulation. This

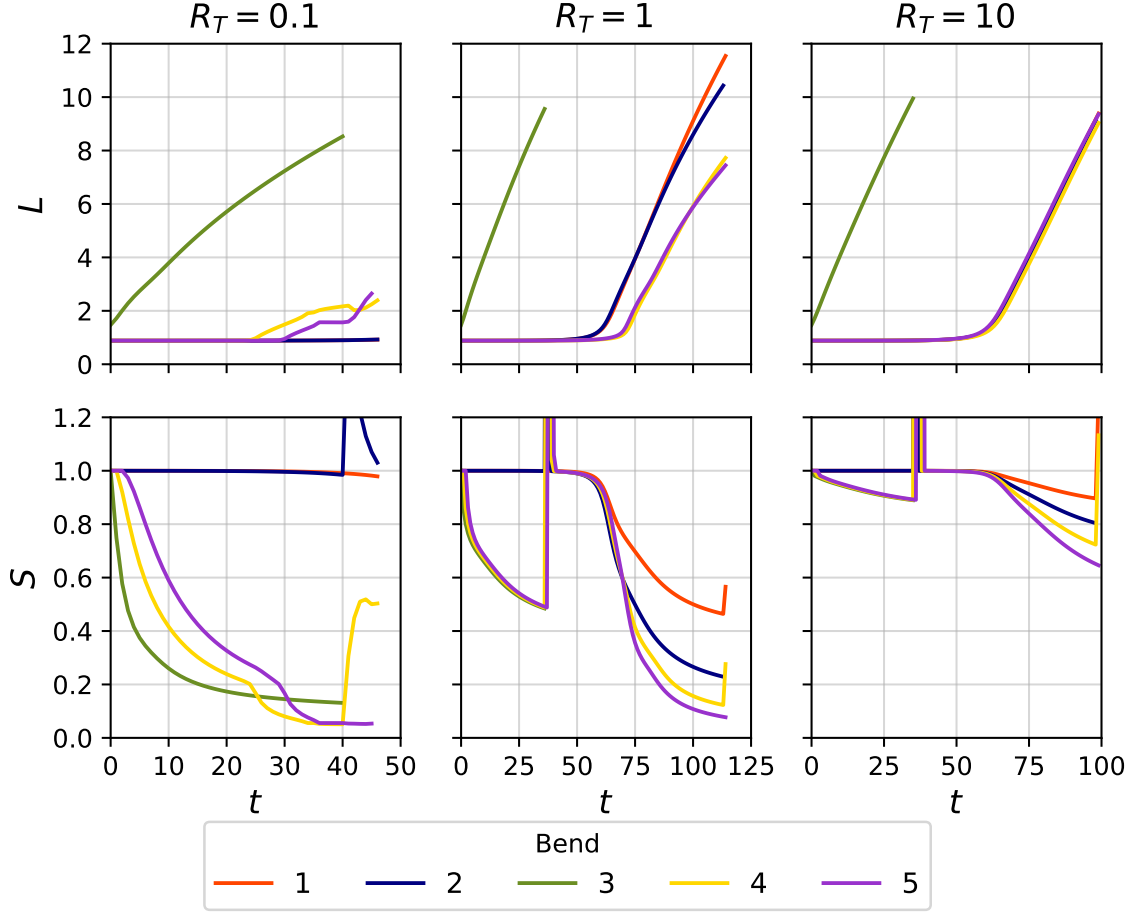


Figure 34 – Comparison of the evolution in time of a 5 bend system, with the central bend (3) with a higher initial sinuosity ($\lambda = 0.09$ and $\theta_1 = 0.9$), while all the others start from the same quasi-straight condition ($\lambda = 0.15$ and $\theta_1 = 0.01$). The simulation started with initial parameters $\beta = 25$, $\tau_* = 1.5$, $ds = 5 \cdot 10^{-5}$ and $R_p = 50$, with the Engelund and Hansen (1967) transport and resistance formula, corrected for the dunes presence. On the top row are plotted the different values of intrinsic length of the channel axis (L) for the bends, normalized with the average value for the initial condition, while on the bottom row the river bed slope (S) is shown, normalized with its initial value. Each column has a different ratio between the planimetric and bed evolution timescales (R_T) value ranging from 0.1 to 10.

is peculiar, since the only difference between the three simulations is the R_T value, but it shows the sensitivity of the river response to the timescale of evolution of the bed and the planimetry. When looking at S , it is interesting to note that for every simulation before the cutoff only the central bend (3) and the ones downstream that (4-5) are changing their slope

in a measurable way, with obviously dependence on the R_T value. For lower R_T values the reduction will be much larger, but so will be the delay in the slope reduction between the bends, as expected by the formulation of the model. As described by Monegaglia and Tubino (2019), for high values of R_T the bed is able to adapt much faster to the elongation or to changes in the sediment supply, while, for low values of R_T , the bed is so slow that is almost not adapting to the changes in the planimetric configuration.

Another interesting feature of the slope for the simulation with $R_T = 0.1$ is the slope dynamic after the cutoff. In the bend downstream the cutoff (4) the initial increase in S caused by the cutoff is rather small since the reach undergoing a cutoff has low slope and the fourth reach is already elongating, thus reducing the overall effect of the slope increase. However, the slope continues to rise, because its sediment supply was suddenly increased since the upstream reach (2) has higher sediment supply compared to the removed bend, but has also because a higher slope due to the cutoff, since the second bend was still short when the cutoff occurred. Another interesting consideration, albeit being less relevant since the cutoff modelling is still quite rough, is the almost instant decrease of the slope to the initial value after the cutoff occurrence for $R_T = 1$ and $R_T = 10$, signalling the ability of the river bed to adapt quite fast to this overload of the sediment supply, while this is not the case for $R_T = 0.1$.

3.3.2 Analysis of the Sabine River slope

With the complete bathymetry of the Sabine River collected during the field survey described in section 2.3.2, it is possible to analyse the slope of the river and to understand if there is a variability among sub-reaches with different sinuosity. Since it is not easy to define what is the correct slope from a bathymetry, particularly with meanders XSs, it was decided to use the maximum elevation of each XS, which is related to the water surface elevation and so it is much more representative of the actual river slope.

In Figure 35 is plotted the longitudinal profile of the Sabine River, with points spaced

every 20 m. The slope was calculated with a linear regression of the data smoothed with the Savitzky-Golay filter and it just over $2 \cdot 10^{-5}$, almost constant along the entire reach. The central reach however has higher sinuosity $\sigma = 1.45$, compared to the $\sigma = 1.07$ and $\sigma = 1.11$ of the other two reaches. If this results is analysed through the lens of the MT

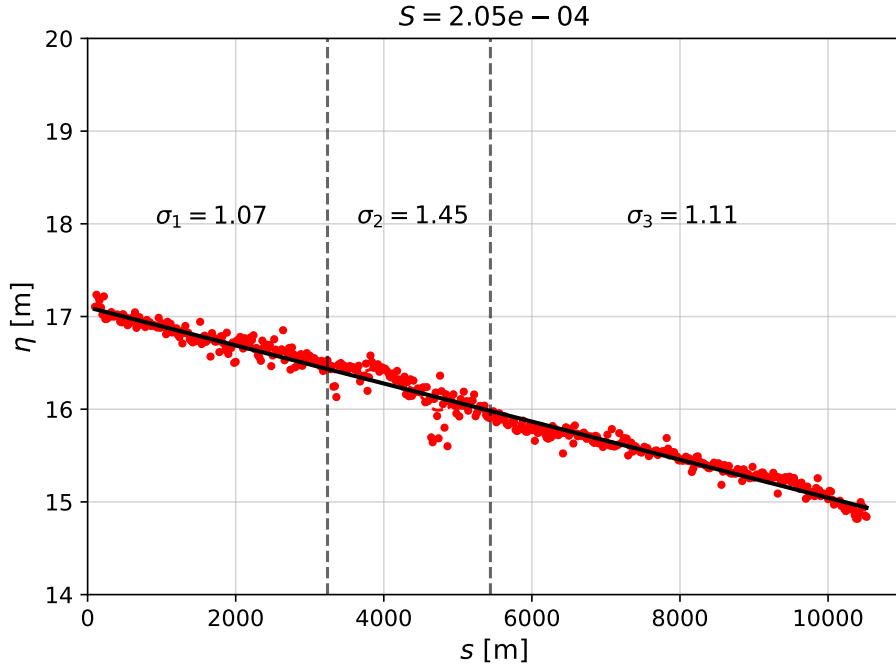


Figure 35 – Longitudinal profile of the Sabine River calculated from the MBES survey with XS spaced every 20 m and calculated as the maximum elevation of each XS. The slope is evaluated with a linear regression of the data smoothed with the Savitzky-Golay filter and is nearly constant across the entire stretch. The total sinuosity (σ) indicated is the sinuosity of each reach, with the central one being the one containing the higher curvature bends.

approach, one can clearly see that having a near constant slope with different sinuosity is the results of a river bed able to adapt faster than the changes to the planimetric configuration, which would mean a high R_T value. Phillips (2003) and Phillips (2008) determined that the surveyed reach was not supply limited and this would entail a fast adapting river bed, with a relatively slow migration, as showed in Figure 28, which calls for a high R_T value, as expected.

The data seems in line with the theory, but it is just a reach of a single river, collected at a certain time and, while being interesting, it is not enough to confirm the theoretical

findings of the MT approach. To be able to prove the aforementioned results, one would need a larger dataset of rivers, preferably surveyed multiple times and with reaches with different stage of evolution, to be able to evaluate the changes in the bankfull geometry and compare it with its planimetric evolution. However, such datasets are not easy to collect and the validation of the MT approach remains an open problem for the future.

3.3.3 *Discussion*

While the proposed approach gives new insights on the evolution of the river bed slopes and in general of the bankfull geometry, it is still far from perfect. The use of the periodic solution limits the representativeness of the simulations, particularly with the cutoff process, since it is highly simplified. The introduction of the ZS solution would allow for real long term simulations, with new bends evolving after a cutoff and a real natural-like behaviour. However, the complexity added by the ZS solution and, especially, the difficulty in treating the boundary conditions effects renders the periodic solution far more effective for testing the theoretical ideas. The use of field data to validate the model is also a relevant step in its development that will need to be carried out in the future. The data collected during this PhD program are a good starting point, but they are too limited to provide a definitive answer. Moreover, the introduction of the width variability would complete the description of the evolution of bankfull geometry and could also give an insight on how to introduce the width variability in the simple model proposed in section 3.2.

Finally, while the effects of the difference in sediment transport is apparent on the evolution of the bends, the bank erosion law is still based on the velocities and is not able to encompass fully the effects of the differences between the transport capacity and the sediment supply of a bend. However, this new approach is a first step towards a more comprehensive modelling framework and the effects of a bend evolution on its neighbours is key aspect to increase the accuracy of the model, particularly for rivers close to the resonant condition, where the bends often transition between the two regimes.

Despite all of these limitations, this new approach is capable of modelling the effects of the changing bankfull geometry on meandering rivers evolution, since it can propagate this changes in time and between bends. Ultimately, this new approach can be used to predict how external forcings alter meandering rivers and how to mitigate the repercussion of these changes, helping river managers and public agency to operate in the most effective way to protect the riverine environment.

3.4 Effects of permafrost on meandering rivers

In the previous sections were described the effects of a changing sediment supply on meandering rivers or the effects of a bend evolution on other bends, however meandering river dynamics are also affected by the floodplain characteristics (Bogoni et al., 2017; Güneralp & Rhoads, 2011) and, during this PhD study, the focus was posed on rivers flowing through permafrost-covered floodplains.

The work described in this section has been carried out in collaboration with Dr. Marta Crivellaro¹ and Dr. Niccolò Ragno² and was published in Ragno et al. (2024). A satellite data based analysis was carried out to find the differences of behaviour between rivers flowing in permafrost covered areas and rivers flowing in a tropical or temperate setting. Moreover, a few considerations on the nuances of modelling this particular rivers will follow, which are more related to the work carried out in this dissertation.

3.4.1 Permafrost signature in meandering rivers

Permafrost meandering rivers have been widely studied for decades (Costard et al., 2003; Douglas et al., 2023; Kanevskiy et al., 2016; Lawson, 1983; Scott, 1978; Tananaev & Lotsari, 2022; Walker, 1998; Walker & Hudson, 2003; Walvoord & Kurylyk, 2016), but the attention has increased in particular in the last few years due to the impacts of climate changes (Brown et al., 2020; Ielpi et al., 2023) on this fragile ecosystem. The

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comparison between permafrost and non-permafrost rivers up until now has often been confined to the analysis of the migration rate, showing that river flowing in permafrost covered floodplains generally move slower than their non-permafrost counterparts (Brown et al., 2020; Crampton, 1979; Ielpi et al., 2023; Rowland et al., 2023). This, however, is a bit reductive, since they are only morphologically active in the summer months and not over the entire year as opposed to non-permafrost rivers. In the work presented in this section the focus was switched onto the differences in the planimetric configuration of permafrost rivers, to see if a permafrost signature exists.

The analysis was carried out using remotely sensed data analysed with PyRIS and the GEE code discussed in section 2.2, to take advantage of the filtering process introduced in that section. The analyses were performed on Landsat data, due to their long time span, but the use of the GEE capabilities enabled also the use of higher resolution Sentinel-2 data, in order to verify the results, particularly in narrow rivers.

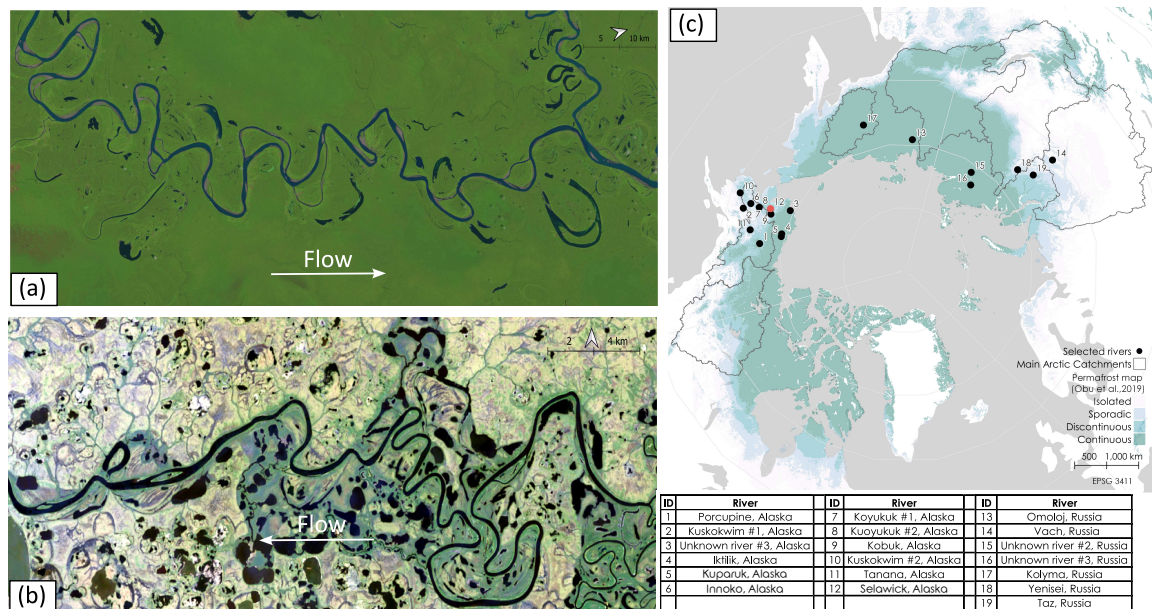


Figure 36 – Examples of typical non-permafrost and permafrost meandering streams with an overview of the investigated study reaches in the Arctic. On the left panels, Landsat images of meandering rivers: (a) Ucayali River, Perú, 5°40' S 74°18' W; (b) the Arctic Selawik River, Alaska (USA), 66°57' N 149°49' W. (c) Permafrost map based on Obu et al. (2019), in which the selected permafrost rivers are highlighted. The red dot indicates the Selawik River. (Ragno et al., 2024)

The non-permafrost data were part of an existing dataset kindly shared by Federico Monegaglia, containing 23 rivers, mainly located in South America, but with some streams located in Africa and other regions. The permafrost data were collected specifically for this study on 19 rivers spread between the North American and Russian arctic regions, as show in the map plotted in Figure 36. The main characteristic of both datasets are reported in Table 6 and Table 8, found in Appendix D, and the entire dataset was published in Bonanomi et al. (2024).

As described in section 2.1.4, the axis curvature is one of the evolution driving parameters in meandering rivers, so naturally it was the first candidate for the comparison. In Figure 37a is reported the distribution of axis curvature for the two classes of rivers, with the curvature ratio of the bend (ν_{bend}) being the maximum value of $\mathcal{C}$ normalized with the average B . The distribution for permafrost and non-permafrost rivers do not present sig-

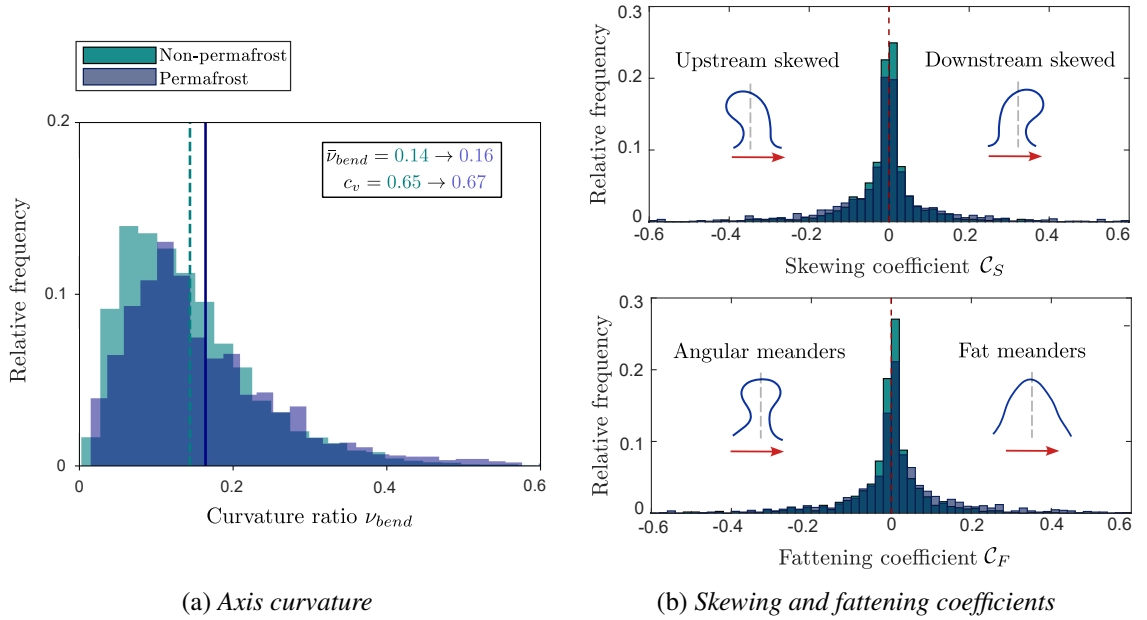


Figure 37 – Comparison between non-permafrost and permafrost sinuous streams in terms of bend-curvature variations. (a) Relative frequency of the dimensionless bend curvature (ν_{bend}). The vertical lines indicate the mean value ($\bar{\nu}_{\text{bend}}$), with c_v being the coefficient of variation (i.e., the ratio between the standard deviation and the mean). (b) Distribution of bend skewing (C_S) and fattening (C_F) coefficients for non-permafrost (teal bins) and permafrost (blue bins) rivers, respectively. The red arrow indicates flow direction. The null hypothesis is verified by means of a Kolmogorov-Smirnov test at a significance level $p < 0.05$. (Ragno et al., 2024)

nificant differences, and this is also corroborated by the distributions of the skewing and fattening coefficients in Figure 37b. These coefficients were extracted using the code developed by Vermeulen et al. (2016) to interpret the shape of meandering rivers as Kinoshita (1961) curves (Equation 4), but they also do not show any meaningful variability. Hence, the difference between permafrost and non-permafrost rivers is not related to the centreline configuration and it is to be searched elsewhere.

Looking at the planimetries of these rivers, however, it seemed that there were sign of a greater width variability, that can be spotted also in the Selawik river in Figure 36. Thus, in Figure 38, are reported the distribution of the amplitude of width oscillation (δ) (Figure 38a), and the width variability between different bends (Figure 38b). The former represent the degrees of width variability inside a single bend, and its distribution in Figure 38a show a higher variability for the permafrost rivers. The latter on the other hand is calculated as the average width of the bends normalized by the “quasi-straight” condition ($\sigma_{\text{bend}} < 1.1$), reported with a box plot per sinuosity class. This second plot shows that per-

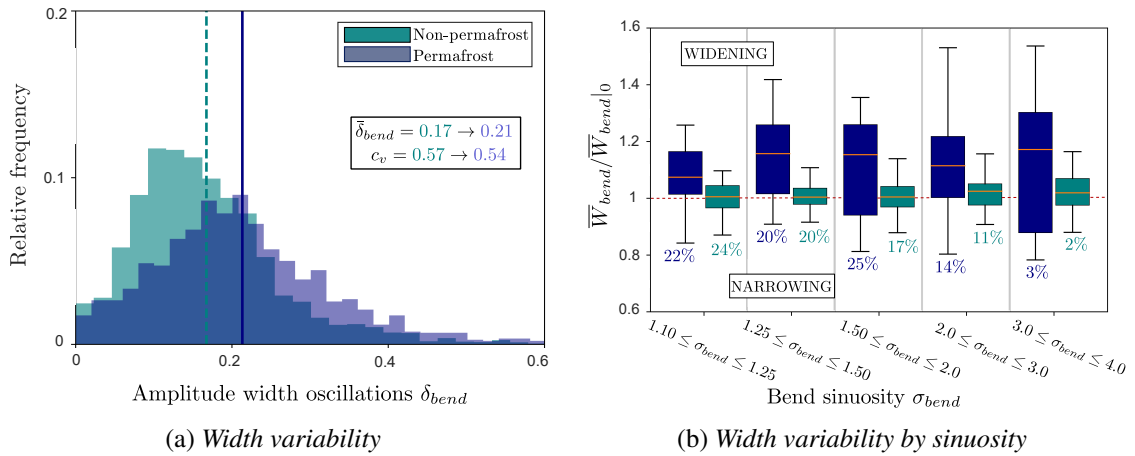


Figure 38 – Comparison between non-permafrost and permafrost sinuous streams in terms of width variations. (a) Relative frequency of the magnitude of bend-width oscillations (δ). The vertical lines indicate the mean value, with c_v the coefficient of variation. (b) Mean bend-width normalized with the “low sinuosity” value for permafrost (blue bins) and non-permafrost (teal bins) rivers. Data are shown for different sinuosity classes. The upper and lower limits of boxes correspond to the lower and upper quartile data values. For each sinuosity class, the percentage of bends within the whole subset is shown. The null hypothesis is verified by means of a Kolmogorov-Smirnov test at a significance level $p < 0.05$. (Ragno et al., 2024)

mafrost rivers have consistently higher width variability compared to non-permafrost ones, in particular increasing their width when the bends elongate, while non-permafrost rivers tend to keep the width nearly constant, in accordance with the findings of Monegaglia and Tubino (2019).

Since Landsat images have a relatively low resolution with 30 m by 30 m pixels, one could wonder if the width variability is connected to subpar river masks, especially in smaller rivers. Using the Sentinel-2 data, which have a 10 m resolution, it was possible to verify that the results were not just caused by the data resolution, analysing a subset of the permafrost rivers among those with the smallest width. As it can be seen in Figure 39, the two distributions are almost identical, which seem to indicate that the width variability is a feature of permafrost rivers and not just something introduced by the employed data or methodology.

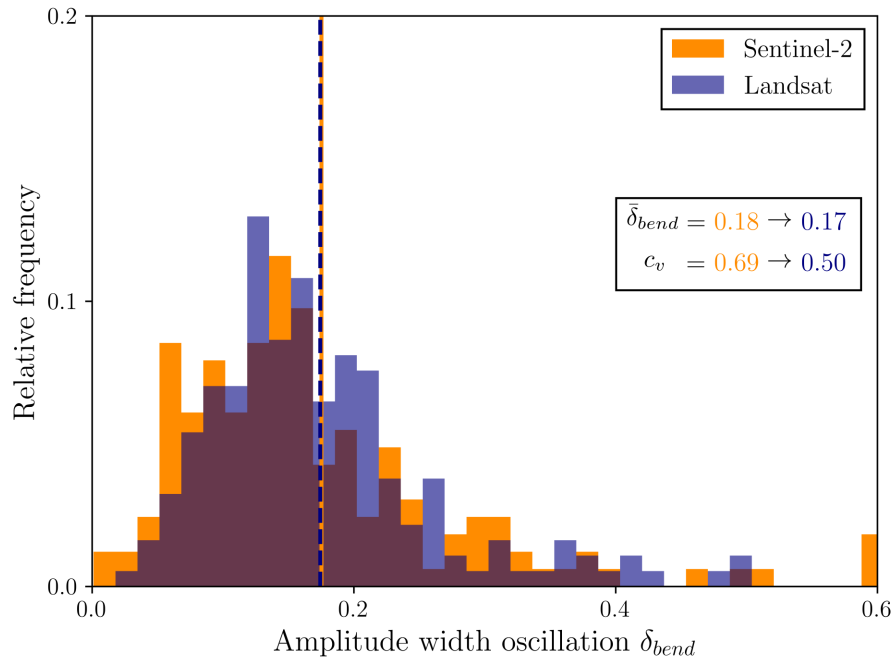


Figure 39 – Comparison between the distributions for the amplitude of width oscillation (δ) for data extracted from Landsat and Sentinel-2 images. The vertical lines indicate the mean value, with c_v the coefficient of variation. (Ragno et al., 2024)

Thus, it seems that meandering river flowing in permafrost covered floodplains do dis-

play a peculiar signature and it is related to the width variability. However, satellite data alone are not able to describe the processes leading to this behaviour. Hence, a new modelling framework is needed to fully describe the evolution of meandering rivers flowing in permafrost covered floodplains and, in the next section, it will be detailed the hypothesis explaining the connection between these results and the different erodibility mechanism of the banks, leading to the results found with satellite data.

3.4.2 Permafrost influence in meandering rivers modelling

From the results of the analysis of satellite data it is apparent the importance of a different approach in the modelling of these particular meandering rivers. Two effects of these width variability need to be considered to properly model the evolution of permafrost rivers.

Firstly, since the relevance of width variability, its effects should be included in the flow field solution. Thus, at the minimum order, it would be necessary to use the linear solution by Repetto et al. (2002) on top of the linear solution for the curvature forcing, as it was done in the model developed by Frascati and Lanzoni (2013). Moreover, it would be beneficial to include also the terms related to the interaction of the curvature and width forcings, as for example described by Luchi et al. (2011).

However, this only explains part of the picture and it does not describe how this configuration emerges in a river. The erosion law proposed in section 2.1.3.1 is not sufficient, since it is not able to represent the symmetric effects derived by the width forcings. Moreover, the hypothesis of a fixed erodibility seems farfetched here because the presence of permafrost influences greatly both the erosion and deposition process. In particular, permafrost thawing produces thermo-erosional niches and localized bank collapses (Costard et al., 2003; Douglas et al., 2023; Kanevskiy et al., 2016; Lawson, 1983; Walker & Hudson, 2003) and these features can generate differential erosion along a bend, leading to the variable width along a single bend. Furthermore, in temperate and tropical climates the vegetation colonizes the freshly deposited point bars (Asahi et al., 2013; Perucca et al., 2007;

Zen et al., 2016) and gives the bar stability, reducing also the erosion in the outer bank. On the other hand, in arctic regions, vegetation is not as fast-growing and deeply rooted (Rowland et al., 2023) and does not control bank stability as much (Chassiot et al., 2020), leading to a slower deposition process and, once the permafrost is thawed, to higher erosion rates, increasing the width differences between bends. Lastly, the hydrological regime, with high floods in the late spring and summer, coincide with the permafrost thawing and ice break-up, speeding up the erosion processes in those few months of morphological activity (Scott, 1978; Tananaev & Lotsari, 2022; Walker, 1998; Walvoord & Kurylyk, 2016). All these factors combined lead to a clearly slower migration (Crampton, 1979; Ielpi et al., 2023; Rowland et al., 2023) compared to non-permafrost rivers, which can probably be ascribed to the short morphologically active window, but it is not necessarily a feature of the permafrost by itself. At the same time, the width variability showed by satellite data can be derived under the hypothesis of differential erosion of the banks and the different speed of the erosion and deposition processes that have been described to happen in those remote lands.

For these reasons accurate modelling of the complex migration processes in permafrost rivers would require the decoupling of the two banks, similarly to what Monegaglia et al. (2019) proposed, with a different erosion and deposition law. The deposition description could be similar to the classical approach described in this thesis, with a lower erodibility coefficient. On the other hand, the erosion law would need to account for the effects of the water temperature and discharge on the permafrost melting and the faster erodibility showed by the banks once they are thawed. Moreover, the differences in erodibility between stretches of the same river must be included in this new erosion law, in order to fully capture the width variability measured in satellite data.

The addition of these effects, which were only described qualitatively in this section, would result in a complete modelling framework able to represent the evolution of meandering rivers in permafrost covered floodplain. While this can appear as a mere academic

exercise, it is worth remembering that permafrost covered floodplain are affected more and more by climate change (Brown et al., 2020; Ielpi et al., 2023) and understanding how they work today will help to describe what will be their future. Knowing also that great amounts of carbon are stored in the permafrost (Zimov et al., 2009), means that rivers can interact with these carbon sinks accelerating its release in a vicious circle that alters the environment even more, which could be accounted for through the proposed modelling framework.

CHAPTER 4. CONCLUSION

This PhD thesis focused on the dynamics of meandering rivers and how these are altered by human activities such as damming, mining and changes in land use across the floodplain, as well as by other external stressors such as the effects of climate change, for example the melting of glaciers and permafrost. During this PhD project, the effectiveness and setbacks of various new and existing ingredients and approaches for modelling meandering rivers were evaluated. However, to achieve this, it was first necessary to understand how meanders function in the absence of external forces, using already existing modelling approaches.

The first step was understanding the bankfull geometry influence on the planimetric configuration of meandering rivers. With the use of the MCMM model, which employs the ZS linear solution for the flow field and bed topography, it was possible to show that the distance from the resonant condition is the main parameter that defines the planform dynamics of meanders, both at the bend and reach scale, regardless the closures employed for the sediment transport and flow resistances. It was already well known that the super- or sub-resonant regime influences the behaviour of meandering bends, as, for example, the migration direction or the bend skewing (Seminara et al., 2001). However, the relationship between the bankfull geometry and the planimetric configuration of meandering rivers was often left aside, because the focus was usually posed only on the planimetric behaviour. In the framework of the analysis of the effects of the changing bankfull geometry, this becomes a key point of this PhD study. With a simple tool based on the resistance and transport formulas, it was possible to derive the effects of the alterations of the sediment supply on the bankfull geometry and, using the aforementioned relationship, also on the planform configuration. While this simplified approach only works for the description of the equilibrium state, the information on the bankfull geometry variability and the differences between the behaviour of gravel and sand bed rivers can be used to understand the

long term consequences of human activities on meandering rivers.

Nonetheless, the analysis revealed a few key deficiencies of the MCMM model, particularly in the comparison between theoretical predictions and the results of the satellite data analysis. Firstly, the model overestimates the total sinuosity, as the range of predicted values does not overlap with that retrieved from satellite data. While not being the scope of this thesis, a few solutions to limit the total sinuosity were considered as, for example, a better representation of the cutoff processes, with a focus on the post-cutoff behaviour of bends. Since the curvature locally increases after a cutoff, the linear model predicts an acceleration of the meander evolution, while field evidence (Richards & Konsoer, 2020; Richards et al., 2022) shows that this is not always the case, as meander bends can stay stationary for decades after a cutoff. Similarly to what Bogoni et al. (2017) proposed, a time varying erodibility coefficient, increasing as the oxbow lakes are progressively abandoned, could reduce the number of bends evolving at the same time, thus limiting the overall sinuosity of the river. Moreover, the presence of flow recirculation cells in the outer bank may hinder the erosion and reduce the elongation of high curvature bends. Field measurements performed on a meandering stretch of the Sabine River are fully consistent with the results of previous laboratory experiments (Blanckaert, 2011) and the effects of the recirculation zones on meander migration were also confirmed by analysing the Sabine centreline evolution using satellite data. While the MCMM model does not account for this effect, it could be included by using a curvature-dependent erosion rate limiter function.

A second weakness of the model is the spatially constant bankfull geometry employed in the MCMM model that clashes with the bend scale dynamics observed from satellite data. During their evolution, meander bends often shift from the super- to the sub-resonant regime (Guo et al., 2019; Zolezzi, Luchi, & Tubino, 2009) as they elongate, ultimately displaying higher sinuosity in the sub-resonant (or upstream skewed) bends. The model however only changes its regime at the reach scale, thus neglecting the effects on the individual bends, and shows higher bend sinuosity for super-resonant bends. This behaviour is

comparable with the behaviour shown by datasets containing exclusively more developed bends (Lagasse et al., 2004; Lopez Dubon et al., 2025), which entail that the super-resonant bends in these datasets are fully developed bend that will not switch regime and are comparable to the fully super-resonant simulations. Even if the model works in this case, the inability to reproduce the bend scale dynamics still limits the model applicability.

To solve these idiosyncrasies, a new local bankfull geometry update was proposed, based on a multi-bend implementation of the MT approach, which is able to reproduce the bend scale dynamics. The introduction of the one-dimensional morphodynamic influence (Monegaglia & Tubino, 2019) shows the effects of an individual bend evolution on its neighbours through the joint effects of the elongation, the changing slope, and sediment supply. For instance, the reduction of the sediment transport caused by the elongation of a bend will also shrink the sediment supply of the downstream bends, with greater impacts for higher bed evolutive timescale. On the other hand, the cutoff occurrence works as a reset button, partially restoring the slope and sediment supply to its initial values, balancing the effects of the elongation. While the proposed implementation of the MT approach is still quite simplified, with the use of the periodic solution and the approximated cutoff description, the new model is able to represent the influence of the sediment supply, and of the bankfull geometry in general, on the bend evolution. Said capabilities are not only useful for the analysis of the autogenic effects of an evolving meandering river, but they can also describe the transitional behaviour induced by changes in the solid and liquid supply caused by allogenic factors. For instance, the construction of dams can trap great amount of sediments, leading to a river that is not able to respond to the slope changes caused by its elongation. On the other hand, a river whose floodplain is undergoing deforestation will have a higher sediment availability, making it able to adapt much faster to slope changes, as shown by the different values of R_T . Lastly, the new local perspective on the parameters update draws attention toward a change in the bank erosion law, towards a more physically based approach. Even though the velocities generally work in describing the bank erosion

of a river at its equilibrium, the local transport capacity could also introduce the effects of an imbalanced sediment yield, which has found to be a driver of the meanders evolution (Constantine et al., 2014).

As a final note on models, a few researchers (Eke, Czapiga, et al., 2014; Frascati & Lanzoni, 2013; Luchi et al., 2010, 2011; Repetto et al., 2002; Zen et al., 2014) have described the effects of the width perturbations in meandering rivers. Although their width remains often somewhat constant (Monegaglia & Tubino, 2019) and the effects of the width perturbations terms are negligible, in specific cases they become relevant (Monegaglia et al., 2019; Zolezzi et al., 2012) and they accelerate the morphodynamic activity Brice (1975, 1982). The increase in width around the bend apex is generally considered caused by an evolution dominated by the bank processes (Zolezzi et al., 2012) and it generally happens in rivers where the two banks evolve at different rate, due to a particularly rapid or slow vegetation colonization of the banks or a particularly slow or rapid bank erosion. While this is not necessary to describe every meandering river, there are a few instances where a more attentive description of the width variability is needed. As described in this PhD work, this is the case of rivers flowing in permafrost covered floodplains, where the relative low cohesion of thawed banks can generate local width differences, which has been recognized as the signature of the permafrost presence. While being a relatively small niche compared to the entirety of meandering rivers, the increasing attention for the arctic regions, the effects of climate change and the potential carbon emission from permafrost thawing (Zimov et al., 2009) renders the ability of studying the long term evolution of these rivers an important task for the future.

In conclusion, the results of this dissertation improve our understanding of the dynamics of meandering rivers under the effects of human activities, such as sediment mining, deforestation, and climate change. Furthermore, this PhD work can help define the possible mitigation strategies for affected rivers, aiding in the preservation of the riverine environment and the beauty of these intricate systems.

APPENDIX A. PERIODIC SOLUTION COEFFICIENTS

Here are listed the coefficient for the periodic solution of the flow field and of the meandering river evolution described in section 2.1.4.4. Since there are some difference with the coefficients are quite close to what reported by Blondeaux and Seminara (1985) and Seminara and Tubino (1992), they are reported for clarity.

A.1 Coefficient for Equations (50-55)

$$a_1 = i\lambda_m + \frac{2}{1 - C_{fT}} \frac{\beta_0}{C_{f0}^{\frac{1}{2}}}, \quad (103)$$

$$a_2 = i\lambda_m, \quad (104)$$

$$a_3 = \frac{\beta_0}{C_{f0}^{\frac{1}{2}}} \frac{C_{fD} - 1}{1 - C_{fT}}, \quad (105)$$

$$a_4 = i\lambda_m + \frac{\beta_0}{C_{f0}^{\frac{1}{2}}}, \quad (106)$$

$$a_5 = 1, \quad (107)$$

$$a_6 = i\lambda_m, \quad (108)$$

$$a_7 = 1, \quad (109)$$

$$a_8 = \frac{r}{\beta_0 \sqrt{\tau_*'}}, \quad (110)$$

$$a_9 = 2i\lambda_m \frac{2\Phi_T}{1 - C_{fT}}, \quad (111)$$

$$a_{10} = i\lambda_m \left(\Phi_D + \frac{C_{fD}\Phi_T}{1 - C_{fT}} \right), \quad (112)$$

$$a_{11} = 0, \quad (113)$$

$$b_1 = -n \frac{\beta_0}{C_{f0}^{\frac{1}{2}}}, \quad (114)$$

$$b_2 = 1 - i\lambda_m k_1 - \frac{\beta_0}{C_{f0}^{\frac{1}{2}}} k_4, \quad (115)$$

$$b_3 = 0, \quad (116)$$

$$b_4 = 0, \quad (117)$$

$$b_5 = k_4 \frac{\beta_0 \sqrt{\tau_*'}}{r}. \quad (118)$$

The coefficients k_1 and k_4 are derived from the flow decomposition proposed by Seminara and Tubino (1989) to include the effects of the secondary circulations when using a two-dimensional vertically averaged model. They are not equal to what is used in the arbitrary curvature solution proposed by Zolezzi and Seminara (2001), albeit they describe the same phenomena.

A.2 Coefficients for the solution in Equations (58-61)

A.2.1 Coefficients for the transverse velocity V_1^m

$$V_0 = \frac{\Gamma_0}{\Gamma_2}, \quad (119)$$

$$V_1 = \frac{\lambda_2^2 V_0 + \Gamma_3}{(\lambda_1^2 - \lambda_2^2) \cosh \lambda_1}, \quad (120)$$

$$V_2 = \frac{\lambda_1^2 V_0 + \Gamma_3}{(\lambda_2^2 - \lambda_1^2) \cosh \lambda_2}, \quad (121)$$

$$\lambda_1 = \left(\frac{1}{2} \left(-\Gamma_1 + (\Gamma_1^2 - 4\Gamma_2)^{\frac{1}{2}} \right) \right)^{\frac{1}{2}}, \quad (122)$$

$$\lambda_2 = \left(\frac{1}{2} \left(-\Gamma_1 - (\Gamma_1^2 - 4\Gamma_2)^{\frac{1}{2}} \right) \right)^{\frac{1}{2}}, \quad (123)$$

$$\Gamma_0 = \frac{a_6}{a_1 a_8} (a_{10} - a_9) \left(\frac{\beta_0}{C_{f0}^{\frac{1}{2}}} + a_2 b_2 \right), \quad (124)$$

$$\Gamma_1 = \frac{1}{a_1 a_8} \left(a_6 (a_3 - a_1) (1 + F_{r0}^2 a_8 a_4) - a_3 a_9 + a_2 a_4 a_6 a_8 + a_1 a_{10} \right), \quad (125)$$

$$\Gamma_2 = \frac{a_2 a_4 a_6}{a_1 a_8} (a_{10} - a_9), \quad (126)$$

$$\Gamma_3 = \frac{a_6}{a_1} \left(\frac{\beta_0}{C_{f0}^{\frac{1}{2}}} + b_2 \left(a_2 F_{r0}^2 (a_3 - a_1) \right) - b_5 (a_3 - a_1) \right). \quad (127)$$

A.2.2 *Coefficients for the water surface elevation H_1^m , the depth D_1^m and the longitudinal velocity U_1^m*

$$H_0 = b_2 - a_4 V_0, \quad (128)$$

$$H_1 = -a_4 \frac{V_1}{\lambda_1}, \quad (129)$$

$$H_2 = -a_4 \frac{V_2}{\lambda_2}, \quad (130)$$

$$D_0 = \frac{1}{a_3 - a_1} \left(-a_2 H_0 - \frac{\beta_0}{C_{f0}^{\frac{1}{2}}} \right), \quad (131)$$

$$D_1 = \frac{1}{a_3 - a_1} \left(\frac{a_1}{a_6} \lambda_1 V_1 - a_2 H_1 \right), \quad (132)$$

$$D_2 = \frac{1}{a_3 - a_1} \left(\frac{a_1}{a_6} \lambda_2 V_2 - a_2 H_2 \right), \quad (133)$$

$$U_0 = \frac{1}{a_3 - a_1} \left(a_2 H_0 + \frac{\beta_0}{C_{f0}^{\frac{1}{2}}} \right), \quad (134)$$

$$U_1 = \frac{1}{a_3 - a_1} \left(a_2 H_1 - \frac{a_3}{a_6} \lambda_1 V_1 \right), \quad (135)$$

$$U_2 = \frac{1}{a_3 - a_1} \left(a_2 H_2 - \frac{a_3}{a_6} \lambda_2 V_2 \right). \quad (136)$$

A.3 Coefficients for the solution in Equations (64-66)

$$A = 2i\lambda (\theta_1 \bar{\theta}_1 \bar{U}_{11} + 9\theta_3 \bar{\theta}_3 \bar{U}_{13}), \quad (137)$$

$$A_0 = -(A_2 + A_4 + A_6), \quad (138)$$

$$A_2 = i\lambda (-\theta_1^2 U_{11} + 3\bar{\theta}_1 \theta_3 \bar{U}_{11} + 3\bar{\theta}_1 \theta_3 U_{13}), \quad (139)$$

$$A_4 = -\frac{3}{2} i\lambda \theta_1 \theta_3 (U_{11} + U_{13}), \quad (140)$$

$$A_6 = -3i\lambda \theta_3^2 U_{13} \quad (141)$$

APPENDIX B. SABINE RIVER GRAIN SIZE DISTRIBUTION

In Table 1, which is found in section 2.3.2, are reported the main diameters for the distribution of every point sampled on the Sabine River with their position, while in this appendix are reported the grain size distribution for each point sampled in Table 2. For each point are reported the % in weight for each grain size between 31.50 mm and 0.063 mm and the % finer than each grain size. The last row reports the % in weight and the % finer of the fraction finer than 0.063 mm.

Table 2 – Grain size distribution for each point sampled on the Sabine River during the field survey described in section 2.3.2.

d [mm]	WP7		WP8		WP10		WP11		XS68L	
	% weight	% finer	% weight	% finer	% weight	% finer	% weight	% finer	% weight	% finer
31.50	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000
22.40	0.000	1.000	0.039	0.961	0.000	1.000	0.000	1.000	0.000	1.000
16.00	0.000	1.000	0.019	0.942	0.000	1.000	0.000	1.000	0.000	1.000
11.20	0.000	1.000	0.006	0.936	0.000	1.000	0.000	1.000	0.000	1.000
8.000	0.000	1.000	0.009	0.927	0.000	1.000	0.004	0.996	0.000	1.000
5.600	0.000	1.000	0.014	0.912	0.000	1.000	0.004	0.992	0.000	1.000
4.000	0.000	1.000	0.013	0.899	0.001	0.999	0.006	0.986	0.000	1.000
2.800	0.000	1.000	0.008	0.892	0.000	0.999	0.002	0.984	0.000	1.000
2.000	0.000	1.000	0.007	0.884	0.000	0.999	0.006	0.979	0.000	1.000
1.400	0.000	1.000	0.013	0.871	0.000	0.999	0.014	0.965	0.000	1.000
1.000	0.000	1.000	0.024	0.848	0.007	0.993	0.030	0.934	0.000	1.000
0.710	0.001	0.999	0.046	0.801	0.056	0.937	0.072	0.862	0.001	0.999
0.500	0.012	0.987	0.106	0.695	0.315	0.622	0.249	0.614	0.001	0.998
0.355	0.200	0.787	0.267	0.428	0.343	0.279	0.363	0.251	0.007	0.990
0.250	0.598	0.189	0.274	0.154	0.165	0.114	0.184	0.066	0.391	0.599
0.180	0.144	0.045	0.119	0.035	0.077	0.037	0.055	0.011	0.477	0.123
0.125	0.035	0.010	0.029	0.006	0.027	0.010	0.009	0.002	0.102	0.021
0.090	0.008	0.001	0.005	0.001	0.008	0.002	0.001	0.000	0.019	0.002
0.063	0.001	0.000	0.001	0.000	0.002	0.001	0.000	0.000	0.002	0.000
Pan	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000

d [mm]	XS68C		XS68R		XS116L		XS116C		XS116R	
	% weight	% finer	% weight	% finer	% weight	% finer	% weight	% finer	% weight	% finer
31.50	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000
22.40	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000
16.00	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000
11.20	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000
8.000	0.000	1.000	0.000	1.000	0.005	0.995	0.005	0.995	0.000	1.000
5.600	0.000	1.000	0.006	0.994	0.004	0.990	0.003	0.993	0.000	1.000
4.000	0.000	1.000	0.008	0.986	0.002	0.988	0.002	0.991	0.000	1.000
2.800	0.000	1.000	0.014	0.972	0.002	0.986	0.002	0.989	0.001	0.999
2.000	0.000	1.000	0.031	0.941	0.003	0.983	0.001	0.988	0.000	0.998
1.400	0.000	1.000	0.127	0.814	0.013	0.970	0.002	0.986	0.001	0.997
1.000	0.002	0.998	0.294	0.520	0.093	0.877	0.005	0.981	0.004	0.993
0.710	0.025	0.973	0.285	0.235	0.360	0.516	0.017	0.963	0.022	0.972
0.500	0.273	0.700	0.141	0.094	0.340	0.176	0.065	0.899	0.230	0.742
0.355	0.472	0.228	0.047	0.047	0.117	0.059	0.238	0.660	0.414	0.328
0.250	0.165	0.063	0.022	0.026	0.029	0.030	0.431	0.230	0.217	0.111
0.180	0.042	0.021	0.015	0.010	0.019	0.012	0.186	0.044	0.083	0.028
0.125	0.016	0.005	0.007	0.003	0.008	0.004	0.036	0.008	0.021	0.007
0.090	0.004	0.001	0.002	0.001	0.003	0.001	0.006	0.002	0.006	0.001
0.063	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000
Pan	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000

APPENDIX C. PARAMETERS USED IN THE SIMULATIONS

In this appendix are reported the initial parameters used for each simulation performed with the MCMM model, divided for gravel and sand bed rivers.

C.1 Gravel bed rivers

Table 3 – Parameters used in the simulations performed for gravel bed rivers with the MCMM model using the Parker (1990) transport formula and the Keulegan (1938) resistance formula.

β	τ_*	d_s	R_p	E
10	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
10	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
10	0.21	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
15	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
15	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
20	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
20	0.21	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
25	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
25	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
30	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
30	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
30	0.21	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
35	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
35	0.21	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
35	0.30	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
40	0.15	$4.5 \cdot 10^{-3}$	3000	$1 \cdot 10^{-8}$
40	0.15	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
40	0.21	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$
40	0.30	$6.0 \cdot 10^{-3}$	2500	$1 \cdot 10^{-8}$

C.2 Sand bed rivers

Table 4 – Parameters used in the simulations performed for sand bed rivers with the MCMM model using the Engelund and Hansen (1967) transport formula and the Engelund and Hansen (1967) resistance formula, with the Wright and Parker (2004) dunes correction.

β	τ_*	d_s	R_p	E
10	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
10	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
15	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
15	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
20	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
20	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
20	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
20	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
25	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
25	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
25	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
25	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
30	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
30	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
30	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
35	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
35	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
35	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
35	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
45	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
45	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
45	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
45	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$

Table 5 – Parameters used in the simulations performed for sand bed rivers with the MCMM model using the Engelund and Hansen (1967) transport formula and the Engelund and Hansen (1967) resistance formula, with the original dunes correction.

β	τ_*	d_s	R_p	E	β	τ_*	d_s	R_p	E
15	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	15	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
15	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	15	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
15	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	15	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
15	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	15	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
20	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	20	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
20	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	20	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
20	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	20	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
25	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	20	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
25	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	25	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
25	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	25	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
25	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	25	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
30	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	25	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
30	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	30	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
30	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	30	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
30	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	30	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
35	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	30	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
35	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	35	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
35	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	35	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
35	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	35	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
45	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	35	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
45	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	45	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
45	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	45	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
45	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	45	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
50	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	45	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$
50	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-7}$	50	2.5	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
50	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-7}$	50	3.0	$7.5 \cdot 10^{-5}$	20	$1 \cdot 10^{-8}$
50	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-7}$	50	3.5	$1.5 \cdot 10^{-4}$	20	$1 \cdot 10^{-8}$
					50	3.5	$1.5 \cdot 10^{-4}$	200	$1 \cdot 10^{-8}$

APPENDIX D. MAIN CHARACTERISTIC OF PERMAFROST AND NON-PERMAFROST RIVERS EXTRACTED FROM SATELLITE DATA

In the following tables are reported the main characteristics of the permafrost (Table 6 and Table 7) and non-permafrost rivers (Table 8 and Table 9) extracted from satellite data. Both datasets are published in Bonanomi et al. (2024) and were used for the comparison between permafrost and non-permafrost rivers (Ragno et al., 2024) presented in section 3.4. All data used in section 3.1 for the comparison with the modelling results are extracted only from the non-permafrost dataset.

Table 6 – Main characteristics of the permafrost rivers dataset extracted from satellite data.

Country	River	Reach	Acronym	Lat. [°]	Lon. [°]	Average width [m]	Average length [km]	Number of planimetries	Number of bends	Migration evaluation
Alaska (US)	Iktilik		Ikt	69.862	-150.853	149	121.38	1	71	No
Alaska (US)	Innoko		Dis	63.607	-157.775	117	126.29	1	77	No
Alaska (US)	Kobuk		Kob	66.967	-157.529	290	55.13	5	81	Yes
Russia	Kolyma		Kol	66.183	151.281	886	150.40	2	19	Yes
Alaska (US)	Koyukuk	Ups	KoU	65.462	-157.155	302	100.02	4	115	Yes
Alaska (US)	Koyukuk	Dws	KoD	65.225	-157.583	352	109.82	3	70	Yes
Alaska (US)	Kuparuk		Kup	69.653	-149.809	166	70.95	2	78	Yes
Alaska (US)	Kuskokwim	Ups	KuU	62.831	-155.606	156	45.02	3	57	Yes
Alaska (US)	Kuskokwim	Dws	KuD	61.551	-160.130	497	63.09	3	22	Yes
Russia	Omoloj		Omo	69.625	132.326	100	60.99	4	192	Yes
Alaska (US)	Porcupine		Por	66.775	-144.194	406	132.85	5	124	Yes
Alaska (US)	Selawik		Sel	66.586	-159.449	162	73.66	4	131	Yes
Alaska (US)	Tanana		Ten	64.871	-149.486	517	87.60	4	43	Yes
Russia	Taz		Taz	64.979	-161.865	343	74.76	2	32	Yes
Alaska (US)	Unknown Alaska 3		UA3	69.658	-161.865	146	64.97	2	72	Yes
Russia	Unknown Russia 2		UR2	71.571	101.828	152	106.15	1	59	No
Russia	Unknown Russia 3		UR3	73.188	97.952	128	95.98	2	138	Yes
Russia	Vach		Vac	61.435	82.179	170	111.78	3	165	No
Russia	Yenisei		Yen	66.511	81.129	2657	224.49	3	6	No

Table 7 – Years of the extracted planimetry for each permafrost river. In the table are also reported the coordinates of the region used for the masks extraction.

River	Reach	Years			Region coordinates [°]			
					N	S	W	E
Iktilik		1985			70.151	69.555	-150.307	-151.234
Innoko		2006			63.703	63.515	-157.276	-158.236
Kobuk		1985	2006	2015	2019	2021	-157.850	-157.177
Kolyma		2019	2021				150.675	152.023
Koyukuk	Ups	1985	1986	2006	2007		-157.612	-156.199
Koyukuk	Dws	1985	1986	2006			-157.756	-157.311
Kuparuk		1985	1986				-150.307	-151.234
Kuskokwim	Ups	1986	2007	2008			-154.977	-155.845
Kuskokwim	Dws	2008	2019	2022			160.757	-159.269
Omoloj		2007	2011	2017	2020		132.198	132.551
Porcupine		1985	1991	2010	2017	2020	-145.274	-143.160
Selawik		1986	2015	2019	2021		-159.814	-159.016
Tanana		1991	2007	2019	2021		-149.830	-149.149
Taz		2007	2020				81.181	82.392
UnknownAlaska3		2015	2020				-162.219	-161.371
UnknownRussia2		2006					101.304	102.203
UnknownRussia3		1986	1998				97.782	98.196
Vach		2006	2010	2015			81.931	83.638
Yenisei		1985	1991	2007			85.911	88.100

Table 8 – Main characteristics of the non-permafrost rivers dataset extracted from satellite data.

Country	River	Reach	Acronym	Lat. [°]	Lon. [°]	Average width [m]	Average length [km]	Number of planimetries	Number of bends	Migration evaluation
Brazil	Araguaia		Ara	-12.857	-50.514	476	252.56	25	582	Yes
Bolivia	Beni		Bni	-13.355	-67.350	380	461.84	21	2363	Yes
Nigeria	Benue		Bue	8.695	10.285	630	189.23	2	20	No
Brazil	Branco		Bra	0.211	-61.771	928	162.28	17	68	Yes
Nigeria	Cross		Cro	5.738	7.977	535	233.22	11	242	Yes
Brazil	Jandiatuba		Jan	-3.869	-68.914	124	234.71	11	1697	Yes
Perù/Brazil	Javari		Jav	-4.211	-70.571	254	262.78	2	162	Yes
Brazil	Jurua		Jur	-5.559	-67.668	323	490.67	4	479	Yes
Indonesia	Mahakam		Mah	-0.305	116.017	236	368.71	5	566	No
Bolivia	Mamore	1	Ma1	-14.736	-65.037	435	229.16	5	235	Yes
Bolivia	Mamore	2	Ma2	-14.639	-65.021	410	245.72	20	1037	Yes
Bolivia	Mamore	3	Ma3	-13.990	-65.108	448	215.51	4	165	Yes
Bolivia	Mamore	4	Ma4	-13.044	-65.051	464	207.88	5	176	Yes
Brazil	Mortes		Mor	-12.543	-50.950	303	281.97	20	1710	Yes
Brazil	Parnaiba		Par	-3.802	-42.679	457	357.50	21	1155	Yes
Brazil	Purus	1	Pu1	-7.704	-65.778	333	284.70	4	262	Yes
Brazil	Purus	2	Pu2	-5.570	-64.254	463	496.56	5	401	Yes
Brazil	Purus	3	Pu3	-4.739	-62.353	661	362.12	2	89	Yes
Brazil	Putumayo		Put	-2.932	-68.567	721	237.34	9	215	Yes
Brazil	Tocantins		Toc	-7.762	-47.820	589	166.63	2	36	Yes
Perù	Ucayali	Ups	UcU	-8.535	-74.280	704	899.56	14	1550	Yes
Perù	Ucayali	Dws	UcD	-6.558	-75.040	658	623.42	12	694	Yes
Brazil	Xingu		Xin	-11.606	-53.565	383	285.24	28	1810	Yes

Table 9 – Years of the extracted planimetrics for each non-permafrost river. Between parenthesis is reported the day of the year when the corresponding Landsat images were extracted.

River	Reach	Years											
Araguaia		1987 (217)	1988 (220)	1989 (206)	1990 (225)	1991 (212)	1992 (215)	1993 (217)	1994 (188)	1995 (207)	1996 (242)	1997 (260)	
		1998 (231)	1999 (218)	2000 (237)	2001 (255)	2002 (242)	2003 (213)	2004 (248)	2005 (234)	2006 (221)	2007 (224)	2008 (243)	
		2009 (261)	2010 (264)	2011 (251)									
		1987 (214)	1988 (201)	1989 (219)	1990 (270)	1992 (164)	1993 (214)	1994 (185)	1995 (204)	1996 (223)	1998 (196)	2000 (178)	
Beni		2001 (212)	2003 (226)	2004 (197)	2005 (247)	2006 (170)	2007 (253)	2008 (208)	2009 (242)	2010 (165)	2011 (168)		
Benue		1984 (309)	1990 (333)										
Branco		1991 (83)	1992 (6)	1992 (158)	1992 (270)	1994 (347)	1996 (17)	1996 (305)	1997 (307)	1998 (70)	2000 (300)	2002 (1)	
		2003 (356)	2004 (39)	2004 (343)	2007 (31)	2008 (98)	2009 (308)						
		1999 (333)	2000 (352)	2003 (8)	2005 (13)	2007 (3)	2007 (355)	2011 (350)	2013 (3)	2013 (355)	2015 (9)	2016 (28)	
Cross		1986 (177)	1988 (215)	1990 (348)	1991 (287)	1992 (34)	1996 (253)	1998 (194)	2001 (282)	2006 (264)	2009 (272)	2011 (230)	
Jandiatuba		1998 (233)	2011 (221)										
Javari		1990 (197)	1997 (232)	2003 (297)	2008 (199)								
Jurua		1988 (54)	1989 (152)	1990 (43)	1997 (350)	2000 (239)							
Mahakam		1989 (205)	1990 (208)	1991 (227)	1992 (206)	1993 (200)							
Mamore	1	1989 (205)	1990 (208)	1991 (227)	1992 (206)	1993 (200)	1994 (219)	1997 (195)	1998 (198)	1999 (201)	2000 (236)	2001 (222)	
Mamore	2	2003 (196)	2004 (215)	2005 (233)	2006 (204)	2007 (223)	2008 (194)	2009 (228)	2010 (183)	2011 (218)			
Mamore	3	1989 (205)	1990 (208)	1991 (227)	1992 (206)								
Mamore	4	1989 (205)	1990 (208)	1991 (227)	1992 (206)	2011 (218)							
Mortes		1987 (201)	1989 (158)	1990 (177)	1991 (180)	1992 (215)	1993 (185)	1994 (188)	1996 (242)	1999 (210)	2000 (213)	2002 (202)	
		2003 (197)	2004 (200)	2005 (218)	2006 (221)	2007 (224)	2008 (211)	2009 (229)	2010 (168)	2011 (219)			
		1989 (274)	1990 (165)	1991 (232)	1992 (267)	1994 (160)	1995 (227)	1998 (235)	1999 (222)	2000 (225)	2001 (219)	2002 (238)	
Parnaiba		2003 (145)	2004 (188)	2005 (222)	2006 (241)	2007 (228)	2008 (215)	2009 (297)	2010 (316)	2011 (231)	2012 (218)		
Purus	1	1997 (193)	2003 (194)	2008 (272)	2011 (232)								
Purus	2	1987 (207)	1994 (210)	2000 (243)	2003 (203)	2007 (278)							
Purus	3	1995 (270)	2011 (298)										
Putumayo		1987 (228)	1988 (71)	1989 (265)	1991 (287)	1995 (234)	1996 (253)	2001 (282)	2004 (291)	2008 (286)			
Tocantins		1993 (130)	2011 (260)										
Ucayali		1990 (225)	1991 (228)	1995 (207)	1996 (194)	1998 (199)	1999 (234)	2000 (189)	2001 (223)	2002 (177)	2003 (268)	2005 (193)	
	Ups	2006 (244)	2009 (228)	2010 (184)									
		1988 (267)	1989 (237)	1991 (203)	1993 (208)	1994 (195)	1995 (262)	1997 (235)	1998 (222)	2000 (212)	2001 (214)	2003 (188)	
Ucayali	Dws	2005 (225)											
Xingu		1984 (207)	1985 (209)	1986 (212)	1987 (215)	1988 (202)	1989 (204)	1990 (207)	1991 (210)	1992 (173)	1993 (199)	1994 (202)	
		1995 (189)	1996 (224)	1997 (194)	1998 (213)	1999 (200)	2000 (219)	2001 (205)	2002 (184)	2003 (211)	2004 (198)	2005 (200)	
		2006 (171)	2007 (206)	2008 (209)	2009 (211)	2010 (166)	2011 (201)						

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