A combined approach to study meander migration in a river of the Bolivian Amazon basin: The Case of the Ichilo River
ボリビアアマゾン盆地における **Ichilo** 川の平面形状変遷に関する研究

By

Kattia Rubi Arnez Ferrel

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Under the guidance of
Professor Yasuyuki Shimizu

Examination Committee:

Professor Yasuyuki Shimizu
Professor Norihiro Izumi
Professor Toshihiko Yamashita

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Hydraulics Research Laboratory
Division of Field Engineering for Environment
Graduate School of Engineering, Hokkaido University

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ABSTRACT

The Amazon basin is constituted by a large river network, where we can find meandering rivers with the fastest migration rates. Most of the studies in the Amazon basin are concentrated in the large tributaries of the Amazon river that have caught the attention of many researchers. Their planform shape and the changes that they experience depend on many factors such as the climate, human interactions, vegetation, etc. However, small meandering rivers in the southern part of the Amazon basin have not been as much studied as the large tributaries of the Amazon river. These rivers exhibit different characteristics compared to the larger tributaries such as short inundation periods and high fluctuation in the water levels. There is still the need to keep studying these rivers in order to answer important questions about their planform characteristics.

This thesis examines the characteristics of a small meandering river in the southern part of Bolivian Amazon: the Ichilo River. The work is based in satellite imagery analysis, field observations and numerical simulations. First, a spatiotemporal analysis is performed using Landsat satellite imagery. Different meandering characteristics such us migration rates, cutoffs, widths, oxbow lakes are qualitatively and quantitatively analyzed in order to understand what are the main controls of meander migration. Water levels collected for a period of 30 years, are statistically analyzed showing patterns with high variability. Planform shapes of the river for along 30 years (1988-2018) show different meandering mechanisms. Cutoffs are plenty observed in the Ichilo, both chute and neck cutoffs, with prevalence of the later. Ten neck cutoffs (1 human-induced) were identified along 150 Km of river reach. This study suggests that neck cutoffs play an important role in the planform development of the Ichilo River. Also, I recognize the effect that El Niño La Niña Southern Oscillation (ENSO) may have played in the migration rates observed in the year 2008 together with another high precipitation event in 2014, after which cutoffs events were observed. As cutoffs were identified as main controls on meander migration a field survey was performed to obtain detailed information in one bend where a cutoff is expected to occur.

The topographic surveys in the river were performed by using a combined methodology of Structure from Motion (SfM) photogrammetry using Unmanned Aerial Vehicles (UAVs) and a Multibeam Echosounder (MBES). Topographic data such as DEMs and orthophotos were obtained with high accuracy in a relatively shorter period of time in the location where traditional topographic works would have been more expensive and riskier. The bank profiles show a river with cohesive banks and dense vegetation with bank failures mainly in the outer banks. Also, the bathymetry shows riverbed scouring in two points in the river: downstream the confluence with the Sajta and in the area located near the port of Puerto Villarroel.

Now consider the current planform shape of the Ichilo River. What are further changes expected in the river? Here, I present a numerical model that captures important characteristics that have been observed from the results of the spatiotemporal analysis (such as neck cutoffs) and the field works to reproduce the trends of meander migrations in the Ichilo River including the development of cutoffs. The model considers the following characteristics: a) Planform shape evolution after cutoff occurrence, b) Profile change due to cutoff occurrence and c) Inner bank accretion and outer migration as a result of the water level variation.

The model is tested in three parts of the Ichilo River, showing its ability to reproduce the trends of meander migration in terms of the planform shape evolution, location of cutoffs and area of abandoned oxbow lakes, being these, one of the first results that show meandering evolution including the development of cutoffs in the Amazon basin. The purposed model can be applied to assess the trend of planimetric changes of meandering rivers at the scale of the Ichilo River due to climate change and/or other perturbations which is important for the communities that inhabit the banks of the Ichilo River.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 INTRODUCTION

Meandering rivers are among the most beautiful patterns that we can observe in nature. These meandering patterns are found in different environments all around the world, and recently also on Mars. They are usually characterized for having one single thread channel with a sinusoidal shape, where the water flows in a succession of opposite bends (Crosato, 2008).

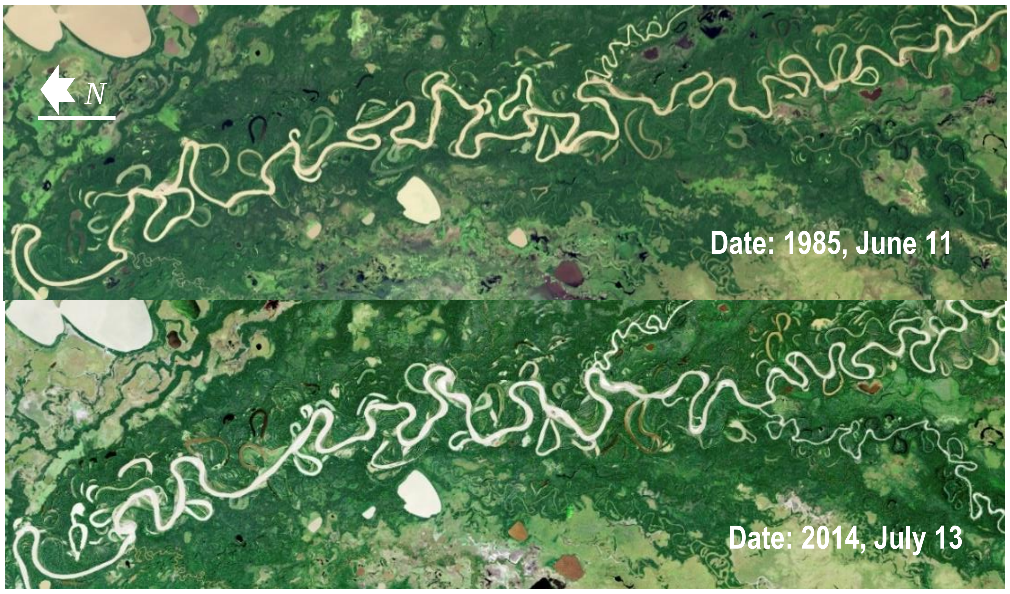

Figure 1.1: Changes in the meander migration pattern observed along 28 years for the Mamore river in Bolivia. NASA Earth Observatory images by Jesse Allen, using Landsat data from the U.S. Geological Survey. Caption by Kathryn Hansen

Meanders have been studied by many researchers (Ikeda, Parker and Sawai, 1981; Crosato, 2008; Parker *et al.*, 2011; D. Motta *et al.*, 2012; Schwenk, Lanzoni and Foufoula-Georgiou, 2015), especially in the last decades. But one place that has attracted a lot of attention is the Amazon basin. The reason relies in the fact that meandering rivers of the Amazon basin are very dynamic and constantly changing their planform shapes. There are even data from meandering rivers such as the Ucayali, where local migration rates of up to 750 m/year were reported along some bends (Schwenk *et al.*, 2017). Figure 1.1 serves as an example of the changes in the pattern of a meandering river in Bolivia, the Mamoré, over 28 years of migration.

In the twentieth and twenty-first centuries, global climate change and its effects on the natural environment are becoming increasingly evident. A large number of investigations demonstrated that changes in temperature and precipitation pattern significantly impact all elements of the environment (e.g. Kiss, 2012), and therefore rivers. The potential effect of climate change on the hydrological regime of rivers represents a concern due to the possible changes that could occur in the river.

An example of this kind of extreme events was observed in 2020 in the Ichilo River in Bolivia. An unusual phenomenon was observed, an inundation that occurred during the dry season in the month of August. Although water level rises are commonly observed during the dry season, inundation is not usual, and 2020 it is probably the only year where flooding was observed two times (the first one occurred on during the rainy season on February 2020). For this reason, it is imperative to continue studying meanders to understand how the river will react to these external perturbations such as climate change.

1.2 MEANDER MIGRATION

Meander migration is mainly the result of an integrated process between the inner and outer bank of a river. Parker et al (2010) said that "in a meander the eroding bank and depositing bank "talk" to each other via the medium of the morphodynamics of the channel center region". Due to the characteristic curved shapes of meanders, the secondary current of the first kind is induced by the unbalance centrifugal force. Therefore, we can observe erosion in the outer bank and eventually will end up in the retreat of the bank. On the other hand, sediment is deposited in the inner bank due to secondary flow, and then, the inner bank accretes forming point bars. This accretion and retreat process allow the meander to grow in amplitude and migrate (Crosato, 2008).

Bank accretion processes depend on different factors such as the material of the bank, vegetation, discharge variability and climate (Asahi *et al.*, 2013). The discharge variability, low flows and high flows, affect the different stages of bank accretion. On one hand, vegetation colonization and soil dewatering occur during low-flow stages and on the other plant eradication and bed erosion occur during high flows (Vargas Luna, 2016).

Crosato (2008) states the important characteristics of a river that lead to meandering are:

- Flow strength: In other words, how much water flows in the river.

- Sediment supply: It is related to how much sediment is entering in the river.

- Bank erodibility: It tells us how easy or difficult it is for water to carry material from the banks.

- Vegetation: How vegetation affects the shape and rate of meandering and its possible effect of bank accretion.

- Frequency of floods: How the frequency as well as magnitude of flood affect the meandering process.

These key characteristics should be studied and their effect quantified when studying meandering rivers.

As meandering rivers migrate, they grow in length and due to their sinusoidal shape they end up overlapping with other bends and cutting the river in what it is known as a cutoff. A cutoff is a natural process often observed in meandering rivers that limit the development of a meander river. Two different types of cutoffs are known, chute cutoffs and neck cutoffs. The occurrence of a cutoffs led to the formation of oxbow lakes. The occurrence of a cutoff reduces the length of the channel that at the same time increase the slope of the channel which can led to changes in the morphodynamics of the river (Schwenk and Foufoula-Georgiou, 2016; Monegaglia and Tubino, 2019; Naito, 2019).

1.3 MEANDER MIGRATION MODELS

Numerical models have become a useful tool to study meandering rivers and have been constantly evolving. A common approach of numerical models for meander migration is to assume that meandering rivers keep a constant channel width such as the model of (Ikeda, Parker and Sawai, 1981). The advance in the literature has shown that width of meander varies as a result of bank erosion and bank accretion processes and that different factors govern both processes (Vargas Luna, 2016) . Since 2011, after the publication of (Parker et al., 2011) some researchers have implemented this framework in numerical models and taking into account the river- width variations. These improvements have resulted in diverse numerical models with different degrees of complexity. The numerical implementation of (Asahi *et al.*, 2013) has demonstrated the abilities of the model to reproduce meander migration in an experimental scale channel. Based on the same framework, (Eke, Parker and Shimizu, 2014) developed another numerical model and applied it to the scale of a meandering river (Vermillion river, Minnesota USA) of 15 m of bankfull width. Still, numerical simulations at a larger temporal and spatial scale (scale of Amazon rivers) are to be explored.

According to Crosato (2008) the modelling of meander migration requires 4 sub-models:

a. Sub-model for describing the flow field and bed topography in curved channels

There are plenty three-dimensional (3D) numerical models that are able to describe the flow in a meanders bends. However, such 3D models are computationally intensive, which makes it unfavourable to model rivers on a large scale of time and space in 3D, especially at the scale of the rivers of the Amazon basin.

b. Sub-model for describing bank erosion

Bank erosion module highly depends on the type of material of the bank: Cohesive or non-cohesive banks. The method of calculations for both the fluvial entrainment and the bank failure will vary accordingly to the type of bank.

So far, simplified models of bank erosion have been used for analysing the failure of banks, due to the complexity of the coupling with a flow field model.

c. A sub model for describing bank accretion

Relatively less studied than bank erosion, because bank erosion is much more important in terms of social and economic impact. Years ago, most of the numerical models assumed the width of the channel to be constant and that considered bank accretion as a function of bank erosion. The importance of bank accretion in meandering rivers, has been recognized and physically based models that include the bank accretion processes have been implemented. In to 2011, Asahi et al presented a bank accretion model by taking into account a critical time that is necessary for vegetation to grow based on the framework of (Parker *et al.*, 2011).

d. A sub model for simulating cut-offs (optional)

If we consider to investigate planform evolution of meandering rivers a cutoff model should be involved.

1.4 MEANDERING RIVERS OF THE BOLIVIAN AMAZON

The Amazon basin covers around 2/3 of Bolivian territory, including the departments of Beni, Pando, Santa Cruz, La Paz and Cochabamba. The rivers in this area are generally meanders characterized for their high discharge. All the rivers from this basin drain their water to the Madeira River, a main tributary of the Amazon River. Main tributaries of the Amazon basin are the Madre de Dios, Orthon, Abuná, Beni, Yata, Mamoré and Iténez and Guaporé. Large tributaries of the Madeira river such as the Mamore and the Beni, have been studied but smaller rivers, especially those in the southern part of the basin, are yet to be investigated. One of these rivers is the Ichilo, a main tributary of the Mamoré River.

1.5 AIM OF THE STUDY AND OBJECTIVES

In this research, I aim to perform numerical simulations of meander migration at the spatial scale of real meanders of the Amazon basin and a short to medium temporal scale (decades) in order to reproduce trends of meander migration. I have chosen the Ichilo River for this investigation. I focus in the planform evolution of meanders and cutoffs occurrence. The numerical model is complemented with a spatiotemporal satellite imagery analysis and data collected during two field campaigns performed in year 2019. The combination of these approaches will give as an integral view of the past , present and future conditions of the river.

1.6 RESEARCH OBJECTIVES

In order to achieve the aim of the thesis we set up the following objectives.

- Understand the history of a small meandering river in the Amazon basin, the Ichilo River (Chapter 2).
- Identify controls on meander migration (Climate change, human-induced modifications) in the Ichilo River by performing a spatiotemporal analysis of the river along 150 Km of river reach and 30 years (Chapter 2).

- Investigate meander migration and bank failure mechanisms in the Ichilo River by collecting information about the bathymetry, water levels and banks by using a combined approach of SfM photogrammetry and MBES (Chapter 3).
- Modify the model of (Asahi *et al.*, 2013) to reproduce meander migration trends including a module to deal with cutoff changes (Chapter 4).
- Apply the model to the Ichilo River (Chapter 4) and analyze the model behavior against field works and satellite imagery data (Chapter 4)

1.7 RESEARCH QUESTIONS

The research questions are summarized in the following diagram:

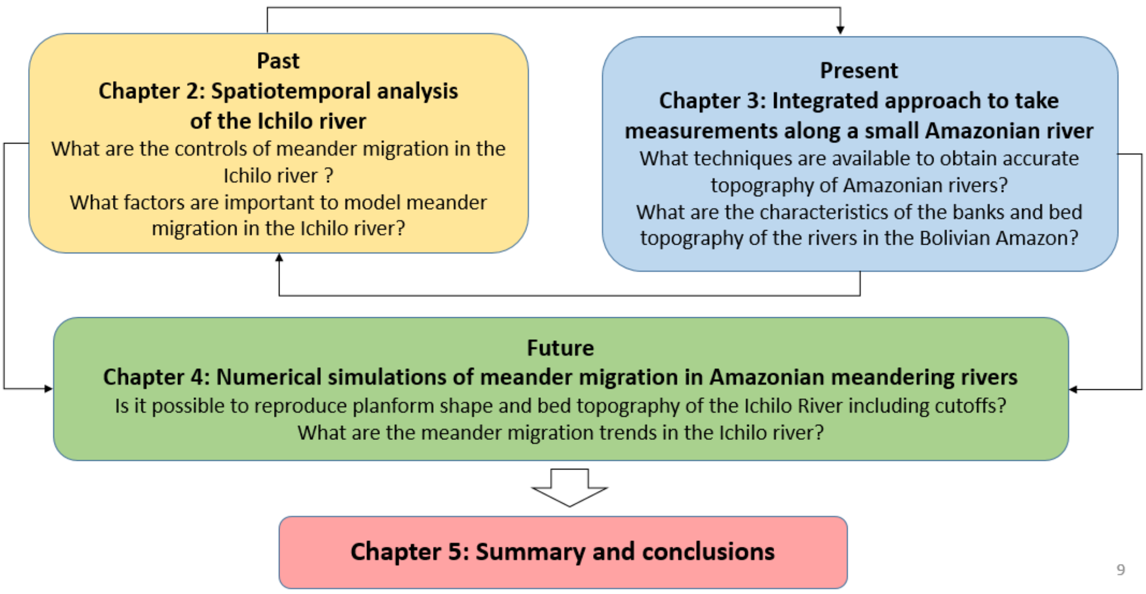

Figure 1.2 Research questions to be answered in each chapter

1.8 THESIS STRUCTURE

The thesis is divided in 5 chapters as follows:

Chapter 2:

In this chapter, I tried to investigate what are the key factors on meander migration of a small meandering river in the Amazon basin, the Ichilo. A spatiotemporal analysis is performed along

30 years and 150 km of river reach. A complete description of the Ichilo River is performed in this chapter.

Chapter 3:

A combined approach of SfM with bathymetric surveys is used in here in order to obtain a complete topography of the Ichilo River. A Pocket Erodometer test is performed to understand the bank erodibility and soil samples are taken in two points in the river.

Chapter 4:

The cutoff module is modified to attain the changes in the bed profile and planform shape adaptation after the cutoff occurrence inside the model of (Asahi *et al.*, 2013). I also apply the model to different parts of the Ichilo River to observe its ability to reproduce trends in meander migration.

Chapter 5:

The last chapter summarizes all the conclusions and future work.

CHAPTER 2: SPATIOTEMPORAL ANALYSIS OF A SMALL MEANDERING RIVER OF THE AMAZON BASIN: THE ICHILO RIVER[1]

Field observations on small rivers of the Amazon basin are less common due to their remote location and difficult access. Here, we show through remote sensing analysis, the planform evolution of the Ichilo River, a small meandering river located in the upper foreland Amazon basin. By tracking planform changes over 30 years we identified the factors that control meander migration rates in the Ichilo River: cutoffs, climate and human interventions. The data suggest that neck cutoffs are the main controls in the Ichilo River and that high precipitation events may have affected migration rates and promoted cutoffs in the Ichilo River. Furthermore, the spatiotemporal variability of meandering migration rates in the Ichilo River is analysed in two locations where neck cutoffs are expected. Finally, the impact of planform changes of the Ichilo River on communities that are stablished along its riverbanks is discussed.

[1] This chapter is a slightly modified version of the article 'Past, present and future of a meandering river in the Bolivian Amazon basin' (2020)' of the J. of ESPL. https://doi.org/10.1002/esp.5058

2.1 INTRODUCTION

The amazon basin exhibits a constantly changing landscape modified by the rivers that flow through its floodplains. There, we can find many of the fastest meandering rivers in the world where cutoffs, oxbow lakes and meandering scars are evidence of the evolution that these rivers have experienced over time.

Numerous riverine communities have been established along the riverbanks of meandering rivers of the Amazon basin. These communities depend on the abundant natural resources available, where their main economic activities include fishery, agriculture and navigation. Although riverine communities show a strong dependency on the river activity (Lombardo, 2016), morphodynamics of meandering rivers are also affected by human activities by even changing their planform shape and bend meander migration rates (Schwenk and Foufoula-Georgiou, 2016). However, it is not only human induced activities that affect the planform configuration of this meandering systems but also natural perturbations. A meander neck cutoff is a natural perturbation that occurs when the river intersects itself (Schwenk, Lanzoni and Foufoula-Georgiou, 2015; Schwenk and Foufoula-Georgiou, 2016), modifying its current planform configuration. Bend development and sinuosity growth are limited by the occurrence of cutoffs (Van Dijk, 2013). Previous studies have demonstrated that neck cutoffs heavily influence the development of meandering river in terms of its planform shape, hydraulics and sedimentology both in the short and long term (Camporeale, Perucca and Ridolfi, 2008; Schwenk and Foufoula-Georgiou, 2016; Li *et al.*, 2020).

Different approaches have been used to understand, quantify and model meandering rivers in the Amazon basin. Researchers have exploited the potential of remote sensing (Lombardo, 2016; Schwenk and Foufoula-Georgiou, 2016; Schwenk et al., 2017; Gomes, Sperandio and Dessart, 2018), field works, and numerical models (Crosato, 2008; Davide Motta *et al.*, 2012; Asahi *et al.*, 2013) to study the planform morphodynamics of these rivers. Each methodology, with their advantages and limitations, highlights the importance of integrating different approaches in a complementary way to investigate meandering rivers whenever is possible (Van Dijk, 2013).

In addition, most of the research carried out in the Amazon basin is concentrated on the main tributaries of the Amazon river (Lombardo, 2016), while the number of studies in small rivers are limited especially in the upper foreland Amazon basin due to their remote location and difficult accessibility. However, large part of the Amazon network is composed by 'small rivers' (Strahler stream order smaller than 7) (Lombardo, 2016). Meandering rivers in the upper Amazon basin that are located close to the Andes range have interesting characteristics such hydrological cycles with numerous peaks around the year (even in the low season), short inundation periods, and high sediment transport regardless their low discharge when compared to rivers of the central and low Amazon basin (Lombardo, 2016; Rejas, 2018). There is the need to understanding the morphodynamics of rivers in upper foreland Amazon basin.

In here, the planform morphodynamics of the Ichilo River, a small meandering river in the upper part of the Bolivian Amazon basin is studied, in order to identify the controls on meander migration and planform evolution such as neck cutoffs, climate and anthropogenic interventions. Here, I discuss about bank erosion and bank accretion processes, previous interventions in the river, the temporal variation of the meander migration rates and future planform evolution of the Ichilo river. Also, I discuss how the changes in the river have and will impact the riverine communities established in the riverbanks of the Ichilo River.

2.2 AREA OF STUDY

2.2.1 Location

The Ichilo River belongs to the upper part of the Amazon basin. It serves a natural border between the departments of Santa Cruz and Cochabamba in Bolivia. The area of our study is show in Figure 2.1.

The Ichilo River meanders from south to north from the Andes range to the Bolivian savannah forest. The river reach of the Ichilo presents a single-thread meandering configuration that starts almost immediately after leaving the Andes Mountains where the alluvial plain starts, and the steep of the terrain decreases noticeably (Peters, 1998).

The Ichilo River is characterized for being an active migrating river with high sinuosity (Lombardo, 2016). Cutoffs, oxbow lakes, paleochannels and meandering scars from old paths of the Ichilo River remain as testimony of this behaviour. Recently, the study of Lombardo et al. (2014) has reported an annual averaged migration rate of 0.034 channel-widths/year, and an average annual width of 134.2±19.35 m for the Ichilo River.

The city of Puerto Villarroel has been stablished along the banks of the Ichilo River and many economical activities depend on them. An important port (Puerto Villarroel) was constructed in this area in the 90's in order to connect the central part with the northern part of Bolivia.

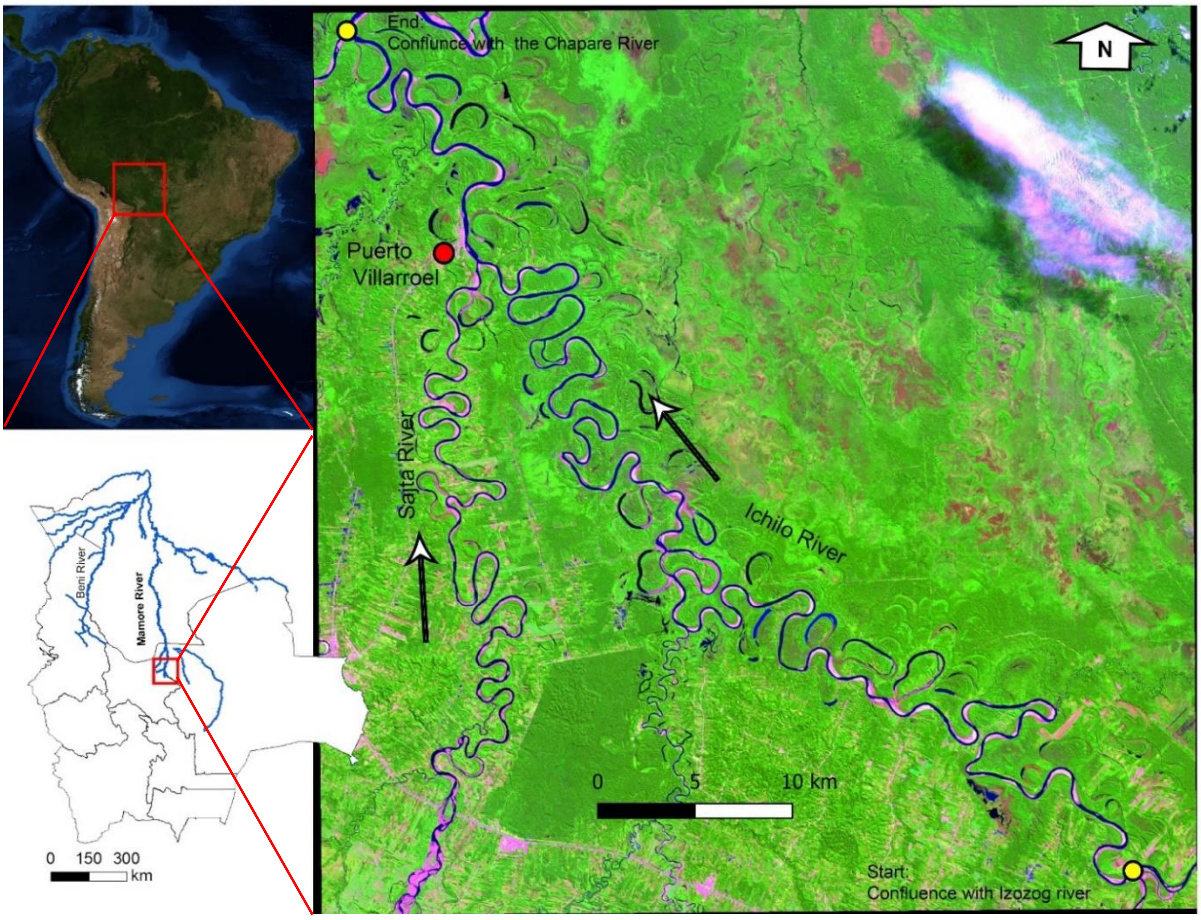

Figure 2.1: Landsat false image showing the location of the Ichilo River and its tributary, the Sajta river, in Bolivia. The yellow dots mark the beginning and the end of the analyzed reach and the red dot the location of the city of Puerto Villarroel in the department of Cochabamba, Bolivia.

2.2.2 Tributaries

The Ichilo River has many tributaries such as the Vibora, Izozog, Isarzama and Sajta rivers among others. The Sajta is the most important tributary of the Ichilo because the river connects with the Ichilo River just before arriving to the city of Puerto Villarroel, where an increase in the width can be observed. The Ichilo River and its tributaries end up in the Mamorecillo river and continues flowing until it becomes the Mamoré River. The Ichilo River is the Andean tributary of the Mamoré River which later joins the Madeira River and then reaches the Amazon.

2.2.3 Human-induced cutoffs

From 1988 to 2018, a total of ten neck cutoffs were observed in a length of 150 km of the Ichilo River. Chute neck cutoffs were also observed but were less frequent than neck cutoffs and most of them were located in large bends. One the neck cutoffs corresponds to a human-induced cutoff designed by Peters (1998) in order to avoid a natural cutoff that was expected to occur during the years of 1996-1997. The objective of this human-induced cutoff was to prevent the recently built port of ‘Puerto Villarroel’ from being left in an abandoned portion of the river (in an oxbow lake) rendering the port useless. This intervention saved the port that have been used by to connect the central and northern part of Bolivia. The comparison of the planform of the river before and after the interventions are observed in Figure 2.2. In terms of abandoned area (area enclosed by the oxbow lake), this cutoff is the largest observed during the studied period. Detailed information on the construction works and designs are explained in the following documents (Peters, 1998, 2009).

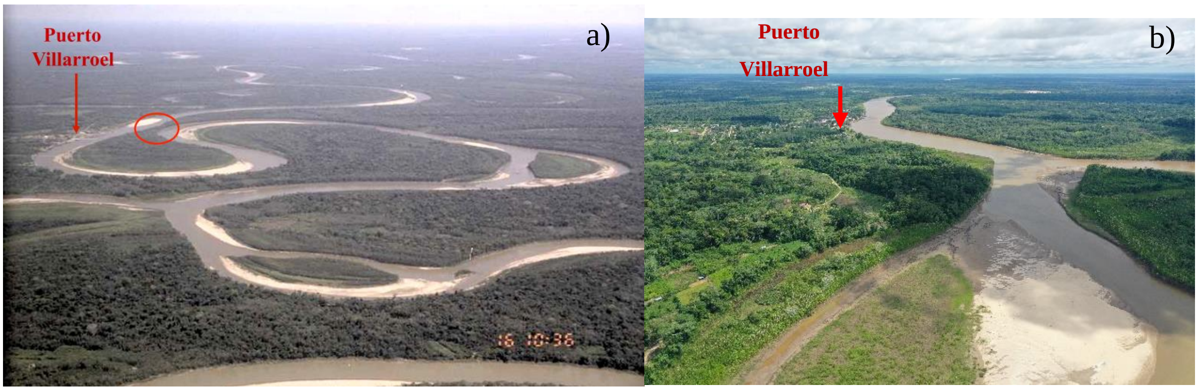

Figure 2.2: Comparison of the evolution of Ichilo River before and after human-induced cutoff. a) Picture taken before the occurrence of the human-induced cutoff, the red circle indicates the location where the natural cutoff was expected. Source: (Peters, 2009) b) Picture taken with drone in February 2019 twenty two years after the human-induced cutoff was executed.

2.2.4 Water levels

The water levels in the Ichilo River show high variability where peaks are observed even during the dry season (June to October) where water levels are at the lowest as illustrated in (Figure 2.3a-c).

Water level data from 1988 to 2019 were analysed and the statistics of the annual water levels are presented in Figure 2.3b. The data set consisted on thirty-one years of daily water levels. Figure 2.3b presents three sets of data: 1) the annual maximum water level (blue asterisks) , 2) annual minimum water levels (red dots) and 3) mean annual water levels (yellow squares). The data show that water levels each year decreased below the 2 meters' level and reach values higher than 6 meters. The data also show that the maximum water levels exceeded the flooding level (7.83 m) affecting the city of Puerto Villarroel with inundations in years 2019-2016, 2014, 2013, 2010-2007, 2003, 1995 and 1992. Daily water levels are collected by local organizations (Servicio de Mejoramiento de la Navegacion Amazonica (SEMENA) and the Servicio Nacional de Hidrologia Naval (SNHN in Bolivia) and the data is available by request. Local news reported that in 2020, the Ichilo River flooded twice in January and August (https://eldeber.com.bo/santa-cruz/rebalse-del-rio-ichilo-anega-viviendas-y-amenaza-a-30-comunidades_167253). As the city of Puerto Villarroel is right next to the banks of the Ichilo River, if the river exceeds the bankfull level the city is immediately flooded as illustrated in Figure 2.4.

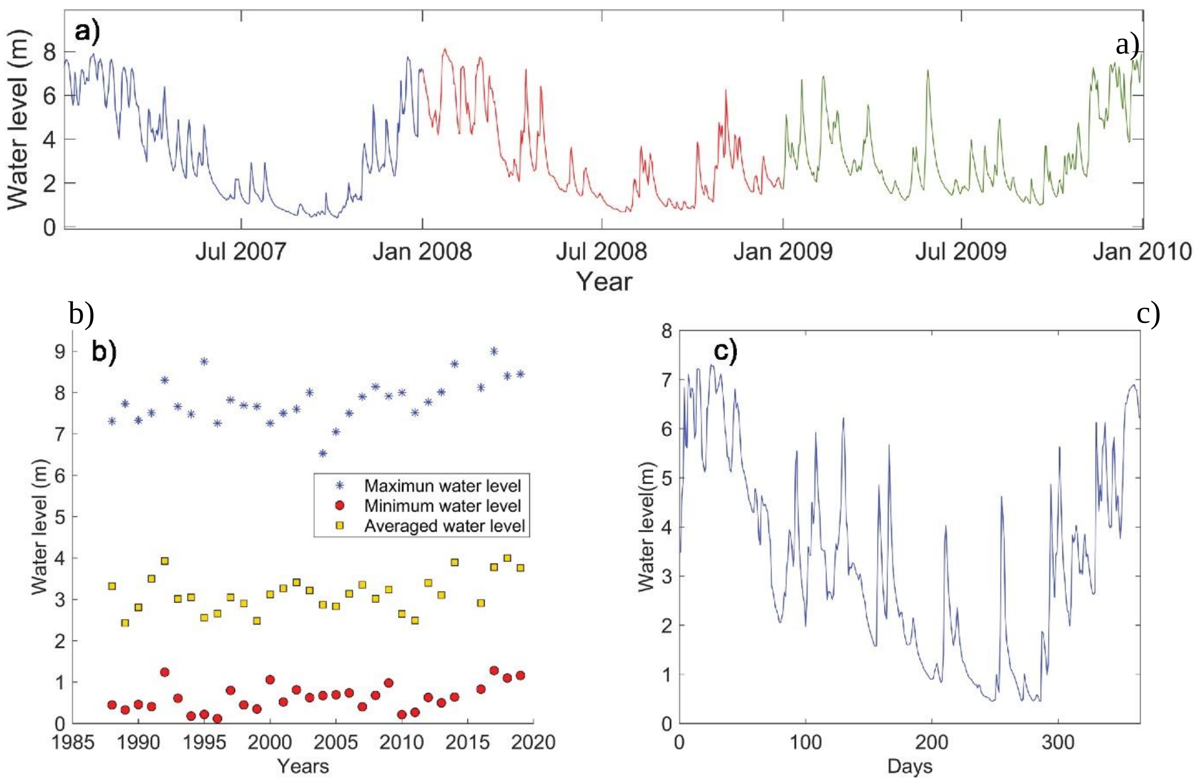

Figure 2.3: a) Water level measurements from January 2007 to January 2010 Source: Servicio de mejoramiento de la Navegacion Amazonica (SEMENA), b) Statistical analysis of water levels, c) Water level variation on year 1988.

Figure 2.4: Left: Flooding in Puerto Villarroel in 2018. Source: Local newspaper 'Los Tiempos' Right: Same point location (El Clipper) during normal stage in February 2019.

2.3 METHODOLOGY

2.3.1 History of the Ichilo River from satellite imagery

Satellite imagery of the area of study of the Ichilo River was downloaded from Lansdat 5 (L5) and 8 (L8) using the Google Earth Engine (GEE) (Gorelick *et al.*, 2017). The analysis started upstream in the confluence of the Ichilo River with the Izozog river and continued along 150 Km along the Ichilo River until the confluence with the Chapare River (Figure 2.1).

The analysis period was from 1988 to 2018, a period of 30 years, and imagery at an annual time scale was downloaded when possible. Each year the satellite imagery was analysed searching for cloud-free images for the area of study for the period of low flow (from June to October) except in year 2008, where we used an image from the month of November. Only cloud-free images were considered in the analysis and the dataset used for the analysis is shown in Table 1.

Table 1 Imagery considered in the analysis

1988	LANDSAT/LT05/C01/T1/LT05_232072_19880619
1991	LANDSAT/LT05/C01/T1/LT05_232072_19910612
1993	LANDSAT/LT05/C01/T1/LT05_232072_19930804
1994	LANDSAT/LT05/C01/T1/LT05_232072_19940807
1995	LANDSAT/LT05/C01/T1/LT05_232072_19950623
1996	LANDSAT/LT05/C01/T1/LT05_232072_19960609
1998	LANDSAT/LT05/C01/T1/LT05_232072_19980717
1999	LANDSAT/LT05/C01/T1/LT05_232072_19990602
2001	LANDSAT/LT05/C01/T1/LT05_232072_20010810

2003	LANDSAT/LT05/C01/T1/LT05_232072_20030731
2004	LANDSAT/LT05/C01/T1/LT05_232072_20040802
2005	LANDSAT/LT05/C01/T1/LT05_232072_20050720
2006	LANDSAT/LT05/C01/T1/LT05_232072_20060723
2008	LANDSAT/LT05/C01/T1/LT05_232072_20081219
2009	LANDSAT/LT05/C01/T1/LT05_232072_20090901
2010	LANDSAT/LT05/C01/T1/LT05_232072_20101006
2011	LANDSAT/LT05/C01/T1/LT05_232072_20110806
2013	LANDSAT/LC08/C01/T1_RT/LC08_232072_20130726
2014	LANDSAT/LC08/C01/T1_RT/LC08_232072_20141017
2015	LANDSAT/LC08/C01/T1_RT/LC08_232072_20151020
2016	LANDSAT/LC08/C01/T1_RT/LC08_232072_20160702
2017	LANDSAT/LC08/C01/T1_RT/LC08_232072_20170822
2018	LANDSAT/LC08/C01/T1_RT/LC08_232072_20180622

2.3.2 Classification of satellite imagery

The classification and the creation of channel masks was performed similar as in Schwenk et al. (2017). The main objective of the imagery analysis was to obtain a well-defined full channel mask of the river for each year. The classification of the imagery followed three steps: training data, classifying and assessment. The first step consisted in collecting training data of the known pixel classes in each imagery: water, vegetation and sediment. Then, the classification was performed using a Support Vector Machine (SVM) classification model. After the classification, a cleaning process was performed manually following the methodology of Schwenk et al., 2017. As a result of the classification, binary images were obtained with a defined channel, and the information was used as input for the analysis of the planform metrics.

2.3.3 Planform analysis

The analysis of the planforms was performed using the River Morphodynamics from Analysis of Planforms (RivMAP) toolbox of (Schwenk *et al.*, 2017). RivMAP consists in a combination of MATLAB codes based on the image-processing morphological operations offered by MATLAB (Schwenk *et al.*, 2017). This toolbox was developed to calculate metrics of meandering rivers from channel masks as input. The following information was quantified with the toolbox: centrelines, banklines, river widths, channel belt, migrated areas, cutoffs, and erosion and accretion rates. More detailed information about the RivMAP toolbox can be find in (Schwenk *et al.*, 2017).

2.4 RESULTS

2.4.1 Mechanisms of meander migration

Figure 2.5 serves as evidence of the changing nature of the Ichilo River, showing the paths where the river used to flow through the last thirty years. Moreover, it helps us to identify the location of the migrated areas and occurrence of cutoffs. As expected in a meandering river, the planform shape indicates that erosion area was larger in the concave parts of the bends while the deposition was observed in the inner part of them. Furthermore, cutoffs were identified and shown in a detailed zoom (Figure 2.5).

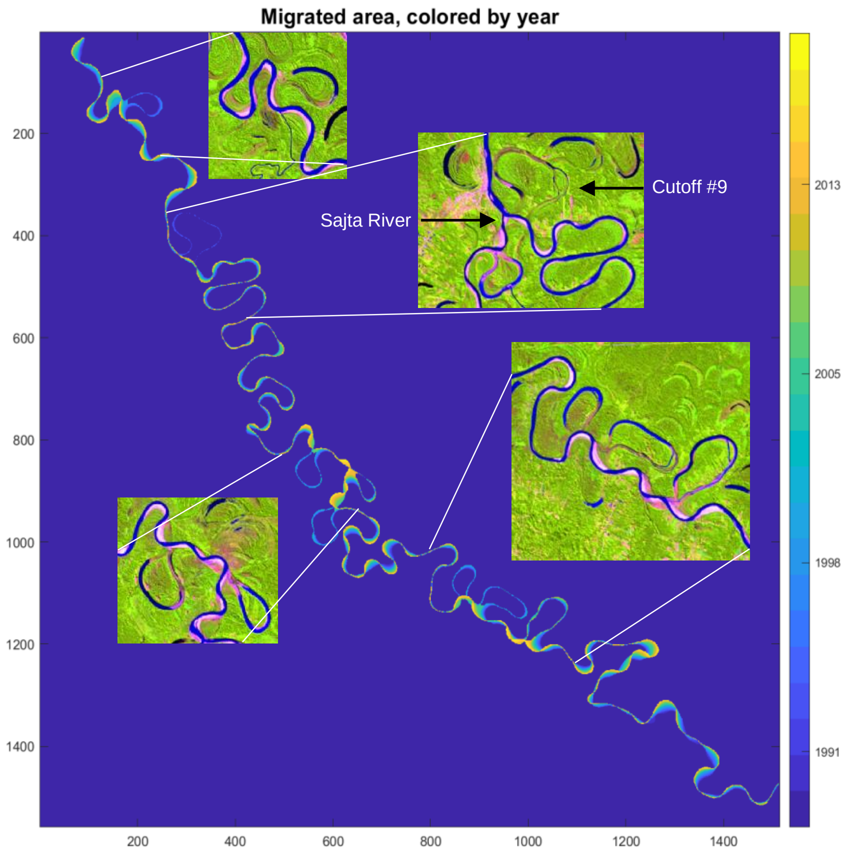

Figure 2.5: Meander migration areas for 30 years period. In zoom, areas where cutoffs where observed

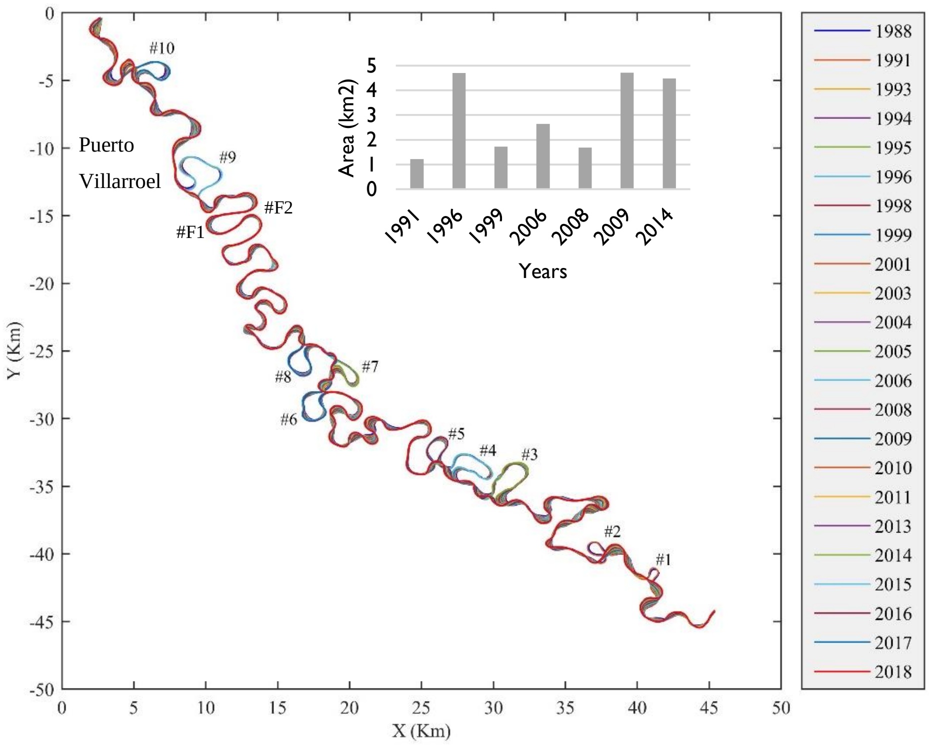

Figure 2.6: Centerline migration and number of cutoffs observed in the Ichilo River. Areas enclosed by the abandoned path due to a cutoff are presented in the graph.

Although both, chute cutoffs and neck cutoffs are observed, the dominant type of cutoff in the Ichilo River was the neck cutoff (Figure 2.5 and Figure 2.6) with a total of ten neck cutoffs in our studied area. The largest cutoff in terms of area observed in the Ichilo River, corresponds to a human-induced cutoff (cutoff #9, Figure 2.5 and 2.6), located near the confluence with the Sajta river. The annual reach averaged migration rates and widths of the Ichilo River for the analysed period is presented in Figure 2.7.

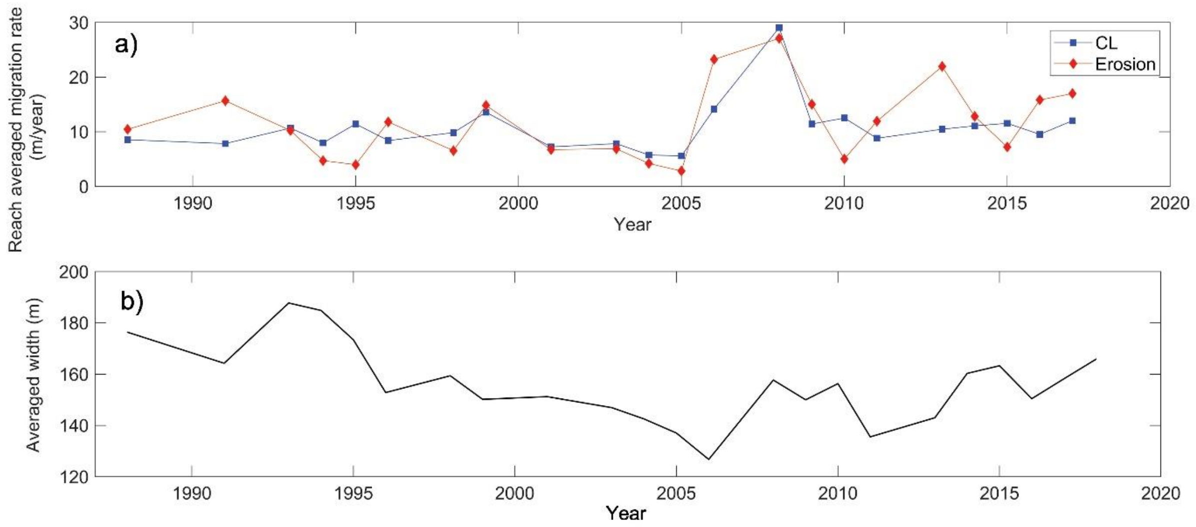

Figure 2.7*:* a) Reach average migration rate per year, based on centreline migration (CL), based on erosion (Erosion) b) Averaged width for the studied period.

An increase in the migration rates is observed from 2005 with a peak that occurred in the year 2008. The spike in the migration rates measured after 2005 seem to correlate with the occurrence of many cutoffs. Four cutoffs were observed between 2007 and 2010 together with an increase in the annual averaged river width as observed in Figure 2.7b. Again, after 2014-2015, two cutoffs were observed and also correlate with increases in the annual averaged river width.

From November 2007 to April 2008 Bolivia suffered a severe season of flooding where the city of Puerto Villarroel was affected by 'La Nina' events. The data indicates that the Ichilo River remained five days flooded in January of 2008, with water levels over the bank level (>7.8 m). Another event of high precipitation was registered on 2014 where water levels remained over the banks for almost 23 days, being these the largest event registered in the 30 years' period. It is possible that the high meander migration rates in 2008 were related to the high precipitation event occurred in that year, and this could have triggered the development of the cutoffs that were observed in the following years.

Similar to the event of 2008, the high precipitation observed in 2014 seemed to have promoted the occurrence of cutoffs and increased of the river width but no change in the meander migration rates were observed. Furthermore, the maximum annual stage (Smax) was plotted against the annual averaged migration rates (Mrcl) (Figure 2.8a) and the results showed a small to moderate correlation (R2=0.16).

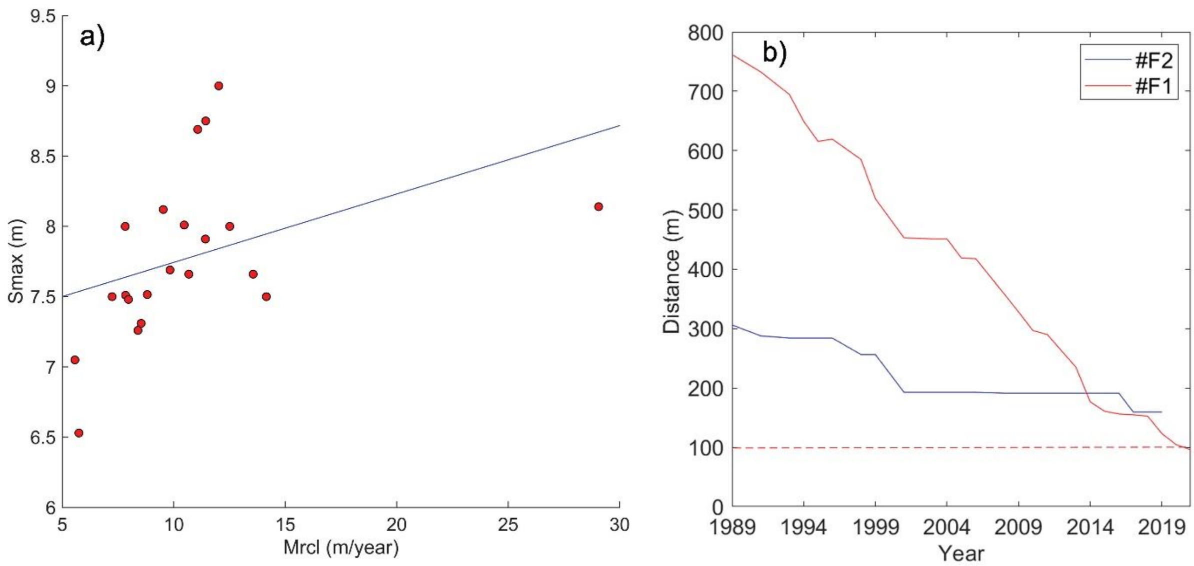

Figure 2.8: a) Correlation between annual maximum stage and migration rates; b) Evolution of the distance before the occurrence of a cutoff event for cutoffs #F1 and #F2

Two points in the Ichilo River, cutoff #F1 and cutoff #F2 (see location in Figure 2.6) were identified to be susceptible to the occurrence of a cutoff. I compared the evolution of the distance before cutoff occurrence in both sections using satellite imagery and the orthophotos. (Figure 2.8b). The graph indicates that the distance in the neck of #F1 has been decreasing at a faster rate than in #F2. The distance in the neck has decreased an 87.4% of the initial distance (761.7m) in 1988, while the neck distance in #F2 has decreased 47.8% only. Our last field measurement (from the orthophotos obtained in May, 2019) showed that the distance left to the intersection and formation of cutoff in #F1 (neck) was of 96.1 m.

2.4.2 Meander belt

The meander belt has important information for flood management and is defined as the area that is supposed to contain all the past channel positions during its long term evolution which in the case of our study is 30 years. This information is important for flood management, oil deposit research and riparian restoration (Camporeale *et al.*, 2005).

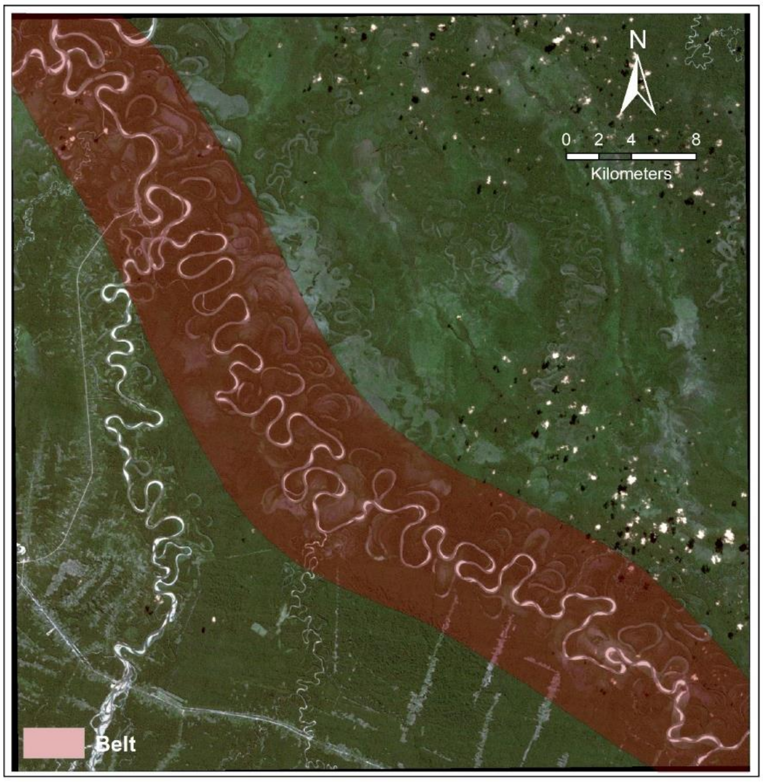

Figure 2.9: Meander belt for the period of 1988 to 2018

The meander belt (Figure 2.9) in general captured all the paleochannels and oxbow lakes observed in the satellite imagery. However, the Ichilo River has been migrating, probably hundreds of years, and in the north-east part of the figure we can observe remains of old channels of the Ichilo that are not contained in the meander belt.

2.5 DISCUSSION

In here, I performed a spatiotemporal satellite imagery analysis to study the planform dynamics of a small meandering rivers: the Ichilo. The results from the satellite imagery allowed us to identify the neck cutoffs as main controls on the planform evolution of the Ichilo River. In addition, the analysis of two bends of the Ichilo River (#F1 and #F2) has shown the spatial variability of the migration rates and the interaction between bends under similar hydraulic conditions. Further changes in the planform shape of the Ichilo River are likely to happen in the short term. I expect the development of cutoff #F1 for several reasons. First, the distance in the neck has been decreasing at a higher rate than in the cutoff #F2 due to the growth of the point bar which narrows the channel and increases the velocity of the flow towards the outer bank (bar push theory) (van de Lageweg *et al.*, 2014). In addition, the satellite imagery showed that the point bar in #F1 is bigger than the point bar in #F2. Furthermore, in the case of #F1, the neck is experiencing erosion from both sides due to the skewness of the bend and geometry of the channel, while in #F2 erosion is occurring mainly on one side. As the distance in the neck decreases, intra meandering flow inside the banks may increase from one bank and that could accelerate the process.

Planform evolution depend on the magnitude and duration of the high and low flow discharges (Asahi *et al.*, 2013). In the Ichilo River, high variability in the water levels was observed. It is expected that the river behaves differently during increasing and decreasing of the discharge affecting the accretion and erosion processes. High and lower flows seem to govern bank accretion, where vertical accretion occurs during floods and transverse point bar accretion during the failing stage and normal flows (Crosato, 2008). Also, heavy precipitation may trigger mass failures along the banks due positive pore pressures that reduce the effective friction angle in the banks (Thorne, 1991) and during the field campaign we observed bank failures which corresponded to the low flows . In our study, annual migration rates showed a small correlation with higher water levels in the river. Similar effect was observed by Schwenk et al. (2017) in his analysis of the Ucayali river and by (Gautier *et al.*, 2010) in the Beni river. The higher annual migration rates in the year of 2008 coincided with La Niña years, which affected Bolivia with extreme precipitation events. The city of Puerto Villarroel suffered inundations from the Ichilo River that lasted five days. As inundation periods in the Ichilo River are usually shorter, a large period of inundation may have affected the strength in the banks triggering bank failures along the Ichilo River. The event of 2014 in which the river was flooded for around 23 days also seem to be related with the increase cutoffs and inundation events after that year.

Human-induced cutoffs observed in the Ichilo and Sajta rivers illustrate the impact of human intervention in the planform development of Ichilo River. The case of cutoff #9, the human-induced cutoff, as a response to a natural neck cutoff that threatened the safety of the port infrastructure, consisted in the design of a new alignment for the Ichilo River and its tributary (Peters, 2009). This design considered a mild curvature at the confluence of the Sajta and the Ichilo River in order to avoid the generation of secondary flows that would promote bank erosion in the riverbanks (Peters, 2009). If the natural meander cutoff had developed the port would have been left in the abandoned path (oxbow lake), eventually became useless (Peters, 1998); and current planform shape of the Ichilo River would have changed to a different configuration.

In addition, areas where the river is stable and has not migrated in the period of our investigation were identified. The inactivity of these areas may be related to the planform spatial variability due to geological reasons (Peters, 1998). For example, the area between the port and the intersection with the Sajta river has maintained the original planform shape since 1988 with minor modifications, even though the PET test showed that the bank material is highly erodible, and according to Peters (1998), this may be the reason why the inhabitants in earlier times decided that location to establish the port. However, even though only minor planform changes were observed in this area, the high resolution bathymetric data (next chapter) showed scour holes in the bed topography in the area near the port and near the confluence with the Sajta river. The collapse of the port at the location of the scour hole, in September, 2019 showed that the bed topography is also changing. The confluence with the Sajta river affects the riverbed morphology by the formation of the scour hole downstream of the confluence and deposition of this material downstream section which can be appreciated in the bathymetric maps in the next chapter (Figure 3.4 and 3.5).

2.6 CONCLUSIONS

The planform morphodynamics and riverbed topography of a small meandering river (Ichilo) in the upper part of the Bolivian Amazon basin was investigated in this chapter. Through spatiotemporal remote sensing analysis, I aimed to understand the factors that control the planform evolution of the Ichilo River. Our results showed cutoffs as main mechanism of planform change of the Ichilo River together with external events: climate and human interventions, particularly heavy rainfalls caused by the ENSO events (‘La Niña’) in the year 2008 showed a small to moderate correlation with the meander migration rates. Another precipitation event in 2014 also seemed to be correlated with planform changes observed in the form of cutoffs.

The spatial variability of meander migration rates was discussed by identifying two points susceptible to cutoffs near to the city of Puerto Villarroel. Cutoff #1 is likely to develop first. The future cutoff development will present further modifications to the ever-changing landscape of the Ichilo River floodplains. The collapse of the platform of the port located in Puerto Villarroel showed the need of bathymetric data and constant monitoring of the river. The lack of data of small rivers located in the upper Amazon basin, such as the Ichilo, calls for more field studies in order to guarantee the safety of the riverine communities that rely on them.

CHAPTER 3: INTEGRATED APPROACH TO TAKE MEASUREMENTS ALONG A SMALL MEANDERING RIVER IN THE AMAZON BASIN[2]

In here an integrated approach that combines structure from motion (SfM) photogrammetry and bathymetric surveys using a Multibeam Echosounder (MBES) is used to obtain bank profiles and underwater features of around 13 kilometers of river length of an Amazonian River (the Ichilo). The studies are complemented with measurements using a Pocket Erodometer Test (PET) and soil samples.

The main objective of this chapter was to collect information for the numerical model in chapter 4, but we also check the accuracy of the proposed methodology showing the potential of SfM with UAVs to study bathymetric and bank features of small meandering rivers with remote location. The field works are supported with pictures taken in the river that help us to discuss bank erosion and bank accretion in a quantitative manner. These techniques have allowed to identify important river morphological features such as erosion the river bed of the river around the confluence area and near the port.

[2] Part of this chapter was used by the author in the paper: Past, present and future of a meandering river in the Bolivian Amazon basin in the J. of ESPL (2020) https://doi.org/10.1002/esp.5058

3.1 INTRODUCTION

Meandering rivers of the Amazon basin have been studied using different techniques such as numerical simulations, satellite imagery analysis, experiments, etc. Field works, however, are relatively scarce due to their remote location and difficult accessibility. In addition, the high discharge of these rivers represent a danger to the technicians, specially during the rainy season, which makes it more difficult and costly to collect data.

In recent years, unmanned aerial vehicles (UAVs) haven been proven to be a cost-effective tool to study different problems in river engineering. Structure from motion (SfM) photogrammetry using UAVs allow to collect data in fast and accurate manner. Different topographic data products can be obtained from SfM photogrammetry such as DEMs, orthophotos, etc. Sometimes, this methodology can even be applied to obtain the submerged topography under clear water conditions, but in rivers with large suspended sediment concentration, such us the Ichilo, this methodology may not be suitable. In such cases, in order to map the underwater terrain features we can combine SfM with traditional methods such us the Echosounders.

In here, we investigate the possibility to use a combination of SfM with a Multibeam Echosounder to obtain topographic surveys in the Ichilo and Sajta rivers. Field data were acquired during two field campaigns performed in the Ichilo River during the rainy season in February and May of 2019, respectively. During the first campaign, orthophotos were collected using unmanned aerial vehicles (UAV), and a Pocket Erodemeter Test (PET) was performed in the banks of the Ichilo River to check the erodibility of the bank material. The objective of this first campaign was to evaluate the conditions to perform a second campaign and obtain more details. The second campaign (May) had the objective to perform a bathymetric survey complemented with SfM photogrammetry to obtain bank profiles.

3.2 METHODS

3.2.1 Structure from motion

During the second field campaign topographic data from the banks were obtained by applying SfM photogrammetry. We surveyed the banks using two UAVs: the DJI Phantom 4 and DJI Mavic Pro. The DJI Phantom 4 was used to take the imagery for the DEM and the Mavic pro was used to take pictures. Before taking the imagery we marked ground control points (GCPs) along the banks. At the beginning we marked GCPs around every 100 m but after the confluence the GCP were taken wherever the access to the area was possible, in order to georeference the digital elevation model (DEM). The GCPs were white crosses (around 1m large) marked using latex painting that were easily visible in the aerial imagery. A total of 44 GCPs were marked along the riverbanks and their coordinates were measured using a Real Time Kinematic (RTK) GPS unit (Figure 3.1). After the GCPs were marked, the UAVs were launched immediately and the pictures were taken including the GCPs. As this place is susceptible for rain, the drones were launched immediately after. The GCPs were washed away by the rain after 2-3 days of rain. The altitude of the flights was around 181.4 m, and the ground sample resolution was of 5 cm with a lateral and longitudinal image overlap of 80 and 75%, respectively. The flight duration was less than 30 minutes. The imagery was analysed and processed using the software Agisoft PhotoScan which compares the imagery and find homologues points in each picture. Thirty GCPs were used to correct the imagery, and the rest used to assess the accuracy of the imagery (See Annex at the end of this chapter). The mean positional errors of the 14 reserved GCPs were 0.003, 0.004, and 0.06 in the x, y and z directions, respectively. The processed imagery taken in May resulted in orthophotos and a DEM covering around 350 hectares of terrain.

3.2.2 Bathymetric Surveys

Underwater features of the Ichilo River were measured through bathymetric surveys. The bathymetric surveys were performed in collaboration with the United States Geological Survey (USGS). An interferometric MBES and an inertial navigation system (INS) was attached to a boat (Figure 3.1) and surveyed along 14 km of the Ichilo River and 2 km of its tributary, the Sajta River. The data can be accessed through the U.S. Geological Survey (USGS) data release website (Kinzel, Nelson and Kattia, 2019) which includes survey point data in the Universal Transverse Mercator Zone 20 South, in meters. The DEM was created at 1 m resolution and was combined with the DEM obtained from the UAV surveys to obtain cross sections of the river.

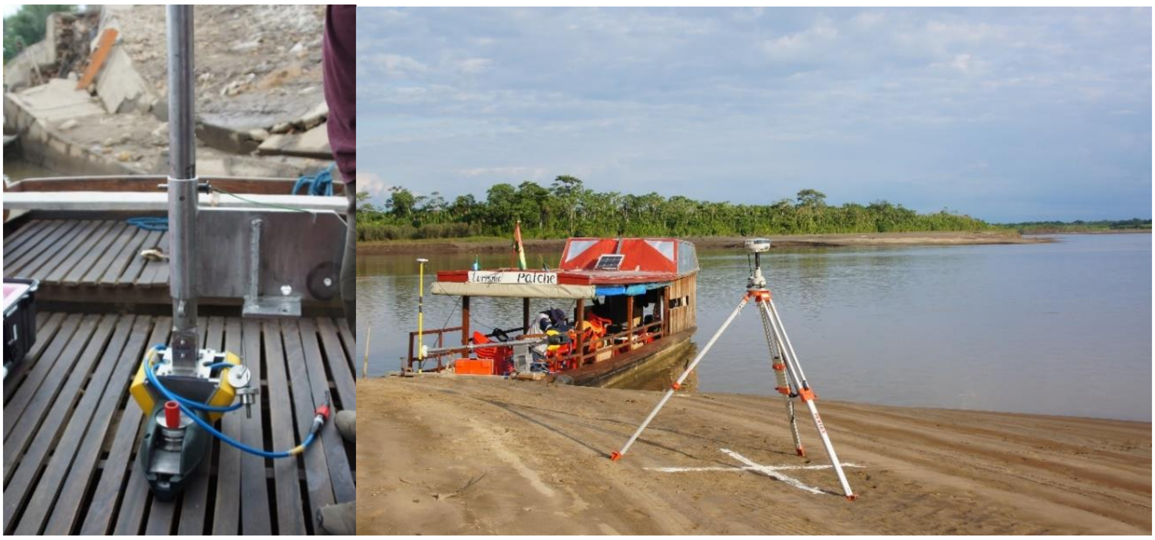

Figure 3.1: MBES equipment installation (left) during field surveys in the Ichilo and RTK GPS (right) used during the field surveys.

3.2.3 Pocket erodometer test

As mentioned before, two field surveys were performed during February and May of 2019 to acquire data. During the first field campaign (February, 2019) we used a UAV to capture photographs along one bend of the Ichilo River where a cutoff is expected. The objective of this campaign was to identify areas of bank erosion by taking orthophotos with the UAV and asses the location in order to perform a second more complete field campaign. Also, field measurements of the erodibility of the bank in the Ichilo River were made by using the Pocket Erodometer Test (PET) (Briaud, Bernhardt and Leclair, 2012). The methodology consisted on shooting a horizontal jet of water in the vertical face of the bank using a mini jet pulse device (a water gun pistol, Figure 3.2). Pulses of water were squeezed at an interval of 1 second with a repetition of 20 times. The depth of the hole was measured using a digital calliper (Figure 3.2).

Figure 3.2 Pocket Erodometer Test in Ichilo River. Right: Minijet pulse device used in the experiment, left: Measurement of the depth using a digital caliper.

The procedure was repeated four times along the bank, and then, the measured depth was introduced in the PET table from (Briaud, Bernhardt and Leclair, 2012)) to determine the erodibility category of the soil. The results are shown in Table 2, where the erosion category was 2 indicating a soil of high erodibility. The detailed methodology of the PET is described in (Briaud, Bernhardt and Leclair, 2012).

Table 2 Measured depths with the PET and erosion category of the soil in the riverbank of Ichilo River

	A	**B**	**C**	**D**	**Averaged**
Depth (mm)	26	25	5.5	18.4	18.7
Erosion category	2	2	3	2	2

3.3 RESULTS

3.3.1 Orthomosaics

The orthorectified image mosaic of a bend of the Ichilo River is presented in Figure 3.3. The effect of the illumination is noticed in the imagery. The imagery taken in February corresponded to a bright and clear day and the pictures were taken in the morning. While the image on the right side shows the imagery were the illumination was not ideal, during the afternoon. The main effect of the illumination was the sun reflection spots in the water. Still, the quality of the imagery is enough to distinguish lines of bank retreat and vegetation features.

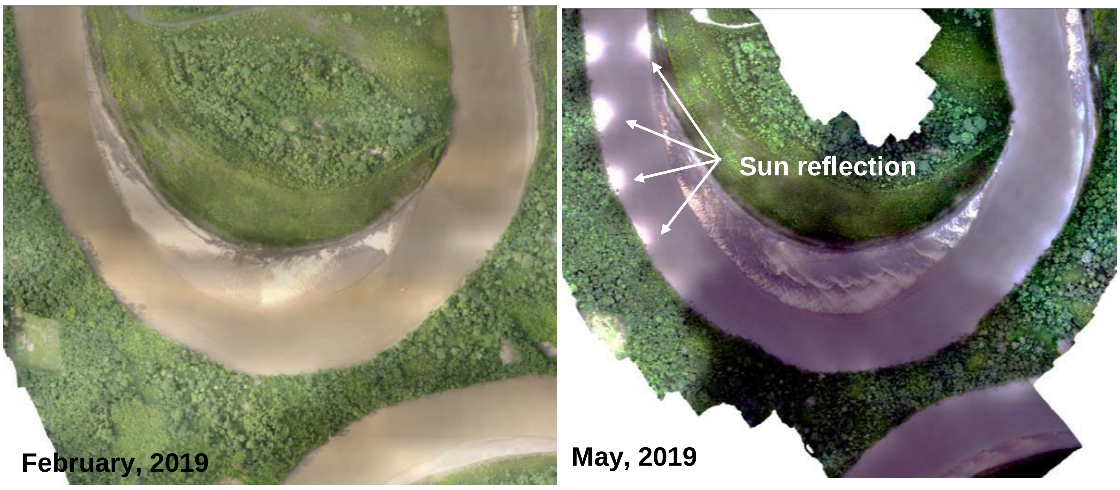

Figure 3.3: Comparison of the orthomosaics obtained during the field trips February(left) and May (right), 2019.

3.3.2 Bed topography

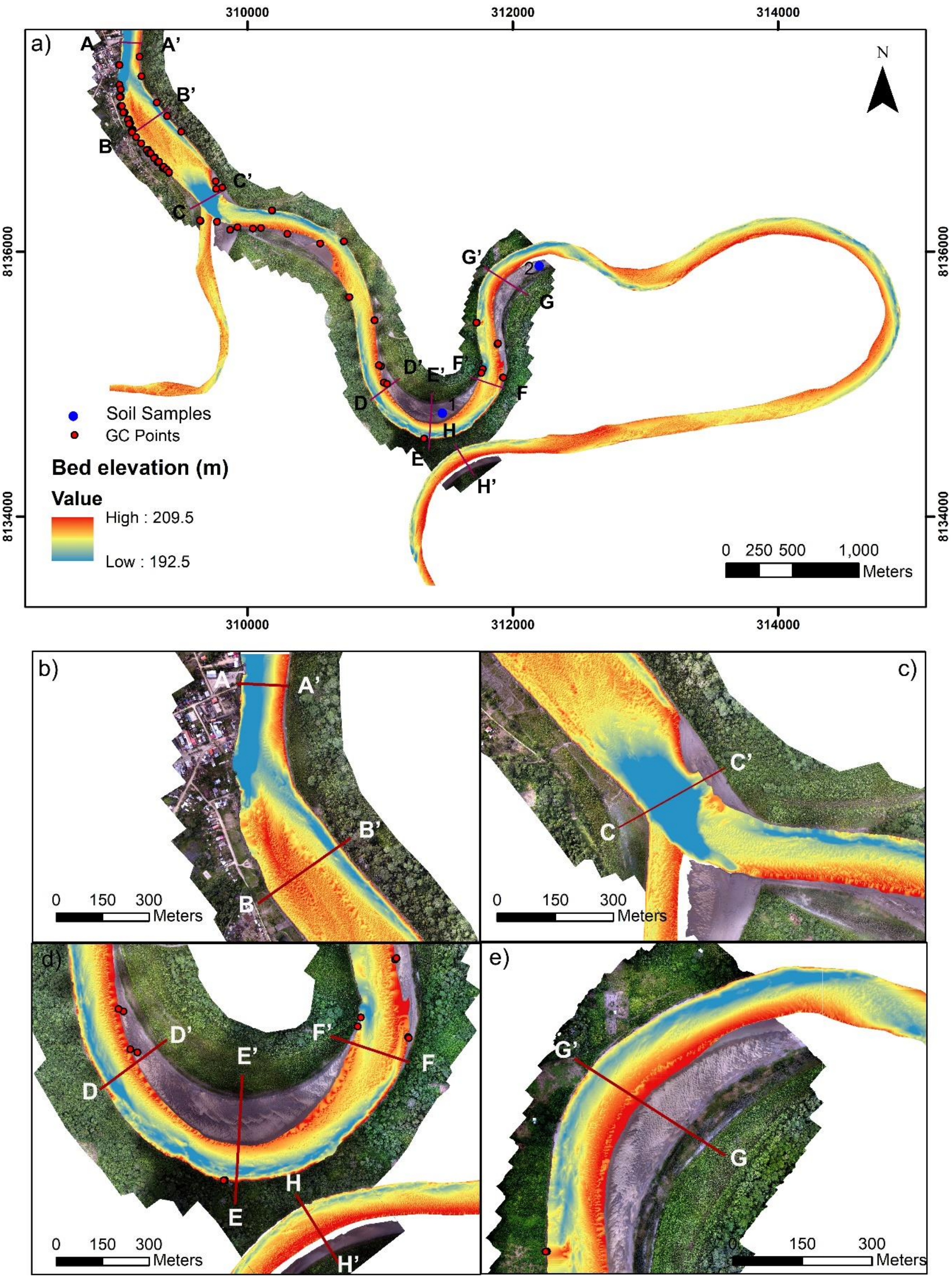

Figure 3.4 Bathymetry obtained with the MBES together with the orthophotos obtained in the month of May (2019). The red dots mark the places where the GCPs were taken and the blue ones the location of the soil samples.

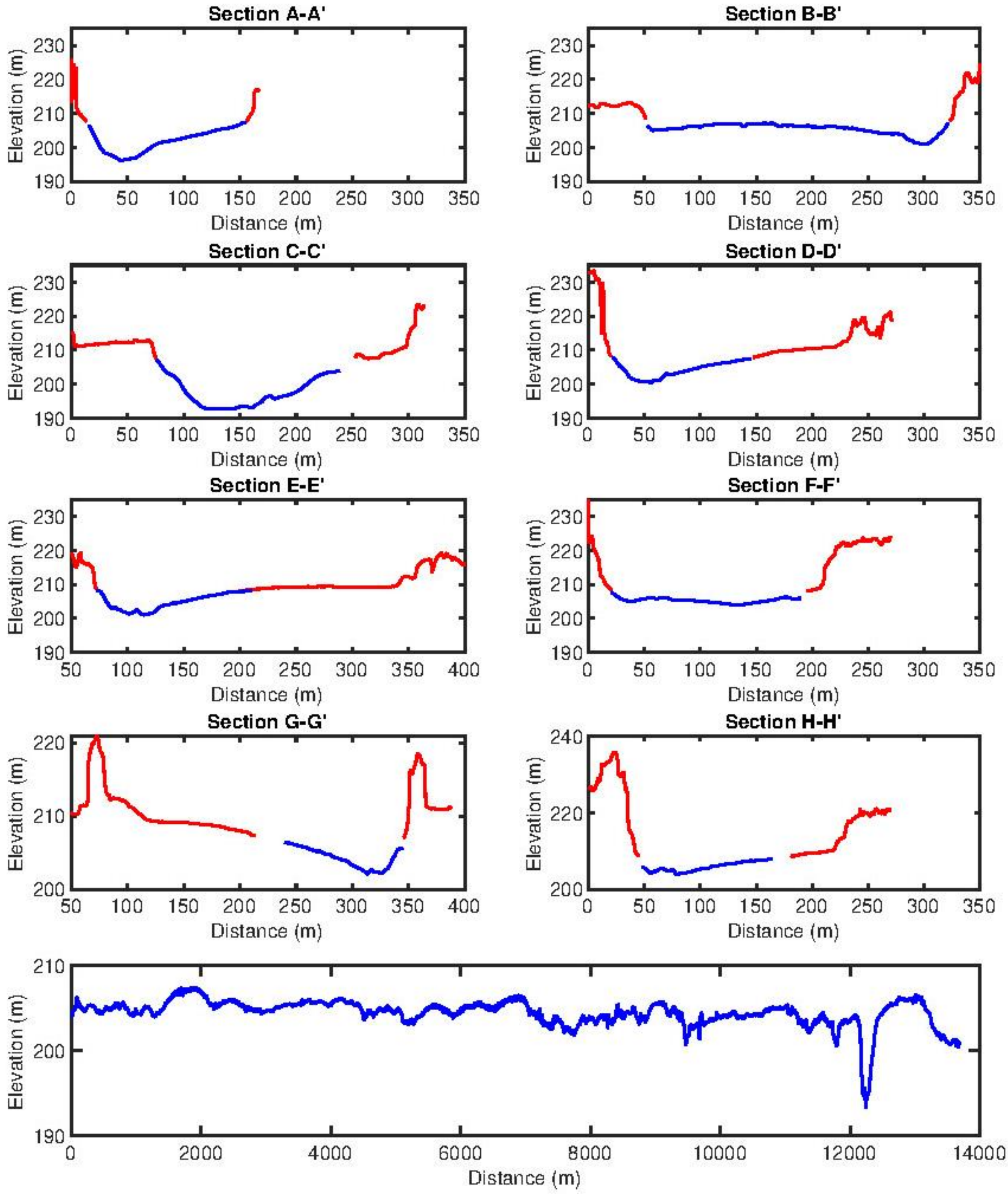

Figure 3.5 River cross sections and bed elevation profile retrieved at different locations along the Ichilo River (see Fig. 3.4 for locations). The y axis shows the elevation and the x axis show the distance. Red lines were retrieved with the UAVs and the blue lines show the bathymetric data obtained with MBES.

Figure 3.4 shows the measurements of the bed topography with the MBES and the orthophotos collected during the second survey. The data from the UAVs and the MBES bathymetry was combined in order to obtain cross sectional profiles of the banks of the Ichilo River, showing high consistency between the results of the UAVs and the echosounder. Some areas could not be surveyed because the boat could not reach these locations due to shallow water and the presence of vegetation that obstructed the access. The maximum water depth retrieved during the measurements was around 14 m near the area of the port. Other point of interest was located downstream of the confluence where the difference of the riverbed elevation of the Ichilo and Sajta rivers was around 10 m (Figure 3.4 near section C-C').

Bank failures were observed all along the Ichilo riverbanks where the deepest part on the riverbed profile was located in the outer bank of the bends. Sections E-E' and H-H'(Figure 3.5) illustrate the cross transversal sections at both sides of the expected cutoff in the river (cutoff #F1). Section H-H' shows the upstream bend and the section E-E' on the downstream part, both bends are separated by a small stripe of land covered by vegetation (forest). A difference of 0.7 m was observed in the riverbed elevation in the outer part of both bends.

3.3.3 Banks and point bars

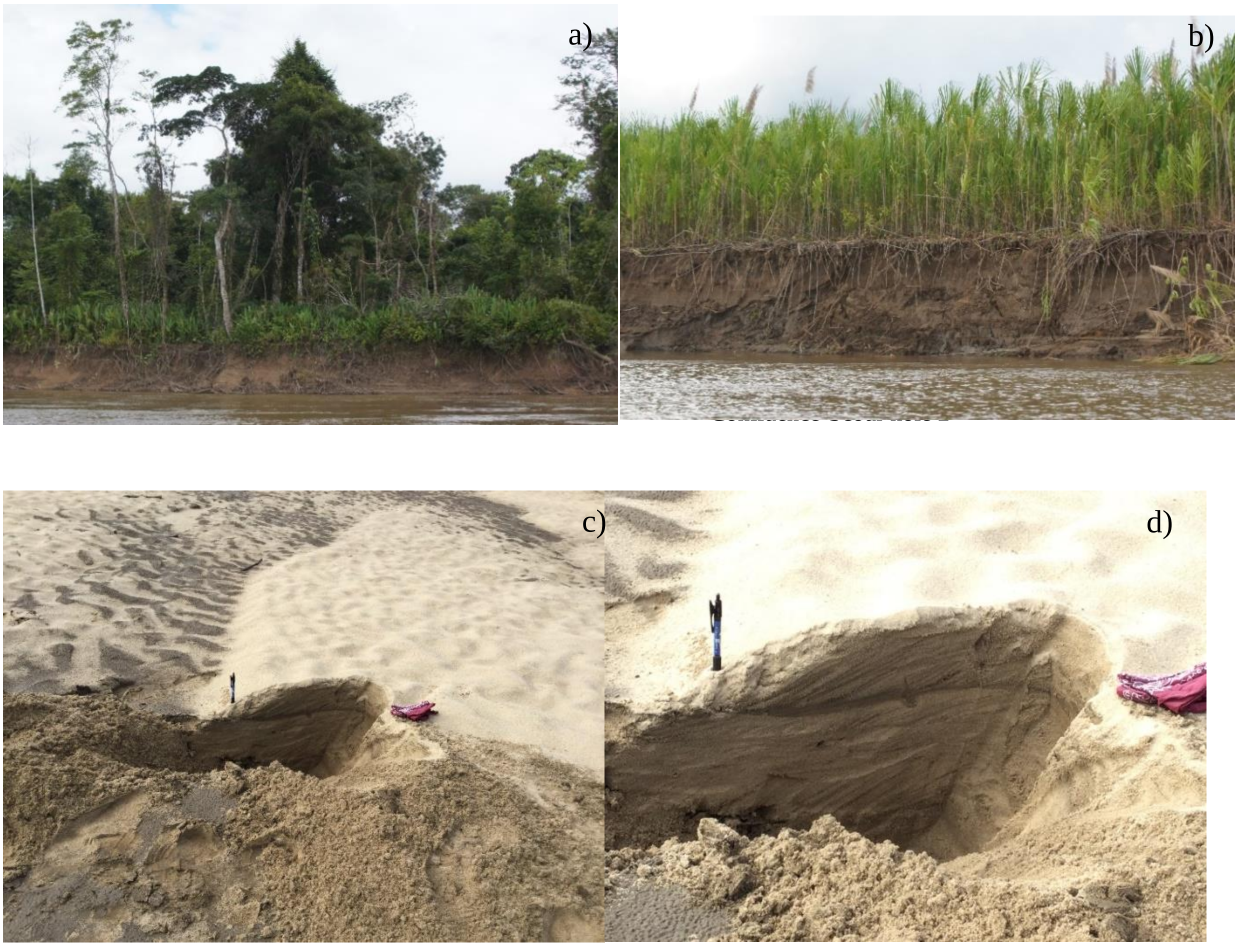

Figure 3.6 Typical banks observed along the Ichilo River; a) Dense forest over cohesive material, b) banks with small bushes, c) and d) stratigraphy in a point bar of the Ichilo River

Bends in the Ichilo River are characterized by showing stable vertical cutbanks constituted of a mixture of cohesive material and fine sand. The PET test suggest that the material in the banks is highly erodible in the area near the port. Upstream the confluence of the Ichilo River with the Sajta river, the floodplain is covered by a dense forest. Inner part of the bends is mainly constituted of fine sand where the vegetation is composed of small bushes. The structure of points bar is presented in Figure 3.6. Excavations made in situ showed two layers of material deposited and clearly separated by a small line of finer material. The location Where the samples were taken are shown in Figure 3.4a, with a mean grain size of D_{50}:0.106 mm (sample 1) and D_{50}:0.210 mm (sample 2).

3.4 DISCUSSION

Upstream the confluence of the Ichilo River with its tributary, the Sajta, the access is restricted and can only be accessed by boat. The UAV-SfM has demonstrated to be a powerful tool to collect high- quality topographic data, bank profiles to be more specific, in places of difficult access. Traditional topographic measurements would have taken more time and cost more. For instance, taking GCPs was relatively easy in areas with no vegetation, but marking them upstream the confluence became more difficult due to the type of material in the banks that mixed with water created a muddy consistency, the vegetation and the verticality of the banks. Point bars were well captured by the SfM photogrammetry. Other elements that also interfered with the photogrammetry were boats that were located in the area near the port. The illumination also played an important role during taking the photography.

The studied area is densely vegetated along the reach between the confluence and the port. The left bank has fewer vegetation because of the settlement of people that live in the area. However, from the confluence to upstream, riverbanks are covered by a dense forest. (Hamshaw *et al.*, 2017) pointed out that the accuracy depends on the density of the vegetation along the bank because they can obscure the ground surface. In here, the vegetation was problematic at the moment of collecting the data particularly in the outer banks than in the inner banks. The outer banks in general were vertical, with planar shear failures observed, that collapsed in front of the bank. In some cases, the recently collapsed vegetation remained in the river interfering with the imagery collected by the UAVs. The collapsed vegetation also interfered with the bathymetric surveys; where debris along the banks posed a hazard to the boat motor and the Multibeam Echosounder. Also, shallow depths did not allow the access of the boat to all the places in the river. Due to this difficulties, several gaps were observed in the bathymetry coverage.

3.5 CONCLUSIONS

In here we applied the potential of SfM photogrammetry with UAV imagery to obtain the bank profiles, and coupled it with a bathymetric analysis using a MBES to obtain the topographic features. The data collected allowed us to generate DEMs and orthophotos and gave us insights of the underwater topography and bank profiles of the river with a high accuracy. The Bathymetric data obtained from the MBES (under water topography) and the SfM bank profiles showed a good agreement. Debris, shallow depths were a limitation at the moment of collecting data which led to gaps in the bathymetric data. The illumination (usually cloudy) and the climatic conditions (constant rain) are factors to take into account in places like Puerto Villarroel.

Although vegetation can create errors in the topographic surveys, this type the methodology shows the potential to use SfM of UAVs in places where the vegetation is present all year round, like the Case of the Ichilo.

The dataset of the bathymetric survey and structure from motion of the Ichilo River is openly available [USGS data release] at ttp://doi.org/10.5066/P9FW6E8K and [Dryad] https://doi.org/10.5061/dryad.jh9w0vt9t, respectively.

CHAPTER 4: NUMERICAL SIMULATIONS OF MEANDERING RIVERS

In here, I modified the model of Asahi et al. (2013) in order to reproduce trends in meander migration in the medium-long temporal and large spatial scale; as large as the scale of Amazonian rivers. The numerical model includes five modules: 1) flow field 2) bed topography, 3) bank accretion, 4) bank erosion, and 5) cutoffs. Mainly, we focus on the cutoff module. The model basically deals with the occurrence of cutoffs including this 3 stages: intersection, planform change and profile adaptation. The model is applied to different parts of the Ichilo River where three cases were tested. The results were compared against field works (Chapter 3) and remote sensing data (Chapter 4). The numerical model was able to reproduce the morphological trends of meandering rivers in the Ichilo River. The modeled planform evolution and bed topography resembled the data from the field measurements in a decadal scale. The numerical model can be used to predict the planform evolution in rivers such as the Ichilo were local communities live around the riverbanks.

4.1 INTRODUCTION

Numerical models, together with remote sensing analysis, field works and experiments, have contributed to explore and improve our understanding of complex dynamic nature of meandering rivers. Along with computer software and hardware development, numerical models have evolved, and nowadays they can reproduce complex phenomena such as flow hydrodynamics, riverbed morphodynamics, and planform evolution of meandering rivers (Ferreira da Silva and Ebrahimi, 2017). Current numerical models couple equations of water with a sediment balance equation (Crosato, 2008), and recently, with bank erosion and accretion equations.

In meander migration models such as the famous of Ikeda et al. (1981), bank erosion is related to the boundary shear stress in the river (Ferreira da Silva and Ebrahimi, 2017) . This type of model considers bank erosion rates equal to bank accretion rates which translates to constant widths. Although this may seem the case in the long term, the river experiences variation in the width as a results of a balance between bank erosion and deposition.

The Bank accretion and bank erosion balance framework of (Parker *et al.*, 2011) has used been used in several models (Asahi *et al.*, 2013; Eke, Parker and Shimizu, 2014). The self-evolving widths in meanders are the result of this balance where bank accretion and bank erosion are calculated independently.

Another important component of meander migration (in the midterm to long term) is the simulations of cutoffs. Cutoffs represent agents of change on the planform shape and the slope of the river which reacts with counteracting mechanisms through aggradation/degradation processes (Schwenk *et al.*, 2017; Monegaglia and Tubino, 2019).

Despite of all the improvements, it is important to remember that numerical models are representation of the reality and they require a lot of input data and parameters (Weisscher *et al.*, 2020). In general, numerical models (Frascati *et al.*, 2010; Asahi *et al.*, 2013) have managed to generate realistic planform shapes with different meandering patterns such as compound bends, downstream and upstream skewed bends, etc. assuming a homogeneous floodplain (Schwendel *et al.*, 2015). However, when comparing the results of numerical model with the reality there have been observed discrepancies (Ferreira da Silva and Ebrahimi, 2017).

Furthermore, previous studies have been applied to reproduce experimental scale channels (Asahi *et al.*, 2013) (width=30 cm) and small rivers (Eke, Parker and Shimizu, 2014) (river width=15m width). Very recently, spatiotemporal analysis of satellite imagery has provided long term datasets to validate the planform evolution of meandering rivers but, this approach limits the studies to two dimensions (2D). It is difficult to assess the reliability of the numerical models proposed due to lack of data and shows the need of complementary field works (Monegaglia and Tubino, 2019).

In here, I explore the possibility of improving the numerical model of (Asahi *et al.*, 2013) in order to simulate the trends on meander migration at the real scale of rivers from the Amazon basin. The model is applied to the Ichilo River, a small meandering river in the upper Amazon basin. The numerical model, was used to simulate three scenarios to study the performance of the model in simulating trends of meandering rivers.

Furthermore, the results from chapters 2 and 3, where cutoffs and oxbow lakes are quantitatively and qualitatively analyzed in a large spatial and long time scale, are used to assess the numerical model. The model is assessed by comparing it with field work data of the cross sections and the riverbed profile. In the following sections we explain the model, the parameters used in the numerical simulations and the main results

4.2 METHODS

4.2.1 Field works and satellite imagery analysis

In here, I use the results of the spatiotemporal analysis from (Chapter 2) and compare it with the simulated results. The planform shape of the river was extracted from the satellite imagery and served as initial planform configuration for the numerical simulations. Oxbow lakes from the satellite imageries were compared with those obtained in the numerical simulations. Also, I use the topographic data obtained from the Ichilo River in May of 2019 to compare it with the numerical simulations of Ichilo River. Cross sections and bed elevation profiles are extracted and used for the numerical simulations.

4.2.2 Numerical model

Numerical models that can reproduce meander migration are usually composed by the following main components: flow field and bed topography of curved channels, bank erosion and bank accretion, and cutoffs (Crosato, 2008). The numerical model of (Asahi *et al.*, 2013) offers these components and therefore was selected for this study. The model includes a module that couples the flow field with a bed evolution model, considers channel width variation and reproduces cutoff development by realigning the channel when an intersection in the channel is observed.

The numerical tests performed in an experimental scale channel demonstrated that the model was able to reproduce flow fields, bed topography and realistic planform shapes using steady and unsteady flow. However, further modifications of the model were necessary to simulate long term simulations at a large scale such us those rivers in the Amazon basin. In here, I modified the model of (Asahi et al., 2013) by improving the cutoff module in order to overcome the sudden changes that were presented by the cutoff in the bed elevation. The bed elevation was smoothed after the occurrence of a cutoff to allow the simulation to continue. A general description of the model is given in the following paragraphs but more detailed information can be find in (Asahi *et al.*, 2013).

4.2.3 Mathematical description

Flow field and bed topography

The flow model uses the two-dimensional depth-averaged continuity and momentum equations that were transformed into a moving boundary fitted coordinate (MBFC) system and are quantified using the following three equations:

$$\frac{\partial}{\partial t}\left(\frac{h}{J}\right) + \frac{\partial}{\partial}\left[\left(\xi_t + u^{\xi}\right)\frac{h}{J}\right] + \frac{\partial}{\partial \eta}\left[\left(\eta_t + u^{\eta}\right)\frac{h}{J}\right] = 0 \qquad (1)$$

$$\frac{\partial u^{\xi}}{\partial t} + \left(\xi_t + u^{\xi}\right)\frac{\partial u^{\xi}}{\partial \xi} + \left(\eta_t + u^{\eta}\right)\frac{\partial u^{\xi}}{\partial \eta} + \alpha_1\left(\xi_t + u^{\xi}\right)u^{\xi} + \alpha_2\left[\left(\xi_t + u^{\xi}\right)u^{\eta} + \left(\eta_t + u^{\eta}\right)u^{\xi}\right] + \alpha_3\left(\eta_t + u^{\eta}\right)u^{\eta} - D^{\xi} = -g\left[\left(\xi_x^2 + \xi_y^2\right)\frac{\partial H}{\partial \xi} + \left(\xi_x \eta_x + \xi_y \eta_y\right)\frac{\partial H}{\partial \xi}\right] - \frac{C_d u^{\xi}}{hJ}\sqrt{\left(\eta_y u^{\xi} - \xi_y u^{\eta}\right)^2 + \left(-\eta_x u^{\xi} - \xi_x u^{\eta}\right)^2} \qquad (2)$$

$$\frac{\partial u^\eta}{\partial t} + (\xi_t + u^\xi)\frac{\partial u^\eta}{\partial \xi} + (\eta_t + u^\eta)\frac{\partial u^\eta}{\partial \eta} + \alpha_4(\xi_t + u^\xi)u^\xi + \alpha_5[(\xi_t + u^\xi)u^\eta + (\eta_t + u^\eta)u^\xi] + \alpha_6(\eta_t + u^\eta)u^\eta - D^\eta = -g\left[(\eta_x\xi_x + \eta_y\xi_y)\frac{\partial H}{\partial \xi} + ({\eta_x}^2 + {\eta_y}^2)\frac{\partial H}{\partial \eta}\right] - \frac{C_d u^\eta}{hJ}\sqrt{(\eta_y u^\xi - \xi_y u^\eta)^2 + (-\eta_x u^\xi - \xi_x u^\eta)^2} \quad (3)$$

where t is time; x, y are axes of an orthogonal coordinates system; ξ, η are axes of a nondimensional generalized coordinate system which is defined as (0 ≤ ξ ≤ 1, 0 ≤ η ≤ 1); ξt, ξx, ξy, and ηt, ηx, ηy are differential metric coefficients between the x, y and ξ, η coordinates; J is the Jacobian determinant for the coordinate transformation, which is defined as J = ξxηy_ξyηx; uξ, uηare velocity components in the ξ and η directions, respectively; h is water depth; H is water surface elevation; g is acceleration due to gravity (=9.8 m/s2); and Cd is a bed friction coefficient given by following equation: $Cd = gn_m^2/h^{2/3}$. Here n_m is Manning's roughness coefficient given by $n_m = d_m^{\frac{1}{6}}/6.8\sqrt{g}$ [Kishi and Kuroki, 1973], where d is the diameter of the bed material. In equations (2) and (3), D_ξ, D_η are terms describing the diffusion of momentum in the ξ and η directions, respectively. More details about the equations can be find in (Asahi *et al.*, 2013).

The bed evolution of the river is calculated as using the Exner equation of sediment conservation as follows:

$$\frac{\partial}{\partial}\left(\frac{z_b}{J}\right) + \frac{1}{1-\lambda}\left[\frac{\partial}{\partial \xi}\left(\frac{q_b^\xi}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{q_b^\eta}{J}\right)\right] = 0 \quad (4)$$

where zb is the riverbed elevation, λ is the posrosity of the bed material (assumed as 0.4 in here and q_b^ξ abd q_b^η are the bed load sediment volume transport rate per unit width in the ξ and η directions, respectively.

The sediment transport rate in the original model was calculated the relation proposed by the Ashida and Michiue (1972). In the present model we have decided to include the formula proposed by Brown (1950).

Bank erosion and bank accretion model

The bank accretion and erosion model is based on the framework of (Parker *et al.*, 2011).

Bank migration is calculated using an integral of the sediment continuity equation in the near-bank region in the cross-sectional direction. Although they have included the effect of slump blocks, we neglected this effect in the simulations for simplicity.

The land accretion model proposed by (Asahi *et al.*, 2013) is based on observations of point bar growth and stabilization which depends on local factors such as climate and type of vegetation. Although more complex bank accretion frameworks have been developed to represent the effect of vegetation in bank accretion and their variable characteristics (Vargas Luna, 2016) , still the simple bank accretion model of (Asahi *et al.*, 2013) proves to be an useful representation to quantify bank accretion because it depends on the hydrological regime in the river (alternation of low and high flows). The model considers bar accretion as time scale factor (T_{Land}). If the grid point remains dry for a period larger than T_{Land} it is supposed to have become floodplain and thus it is removed from the computational domain (Asahi *et al.*, 2013).

Cutoff model

Cutoffs module is an important part of meander migration modelling in the long term because they introduce a sudden change in the planform and in the bed elevation profile of the river.

The model considers that the cutoff occurs when the banklines touch each other. First the model search for points where intersection of banks has occurred. The new bank shape is realigned accordingly and a cubic spline interpolation defines the new shape to assure a smooth transition between the old and new bank. Finally, a re-meshing process of the coordinate system takes place. A new centerline is calculated and the bed elevation is interpolated onto the new coordinate system (Asahi *et al.*, 2013).

The new bank is then interpolated using a cubic spline technique to assure a smooth transition in the banks and the same procedure is used for the bed geometry. This approach was enough to model experimental scale meanders. However, when trying to simulate the real scale meanders the high difference between the bed elevation in both bends led the model to collapse.

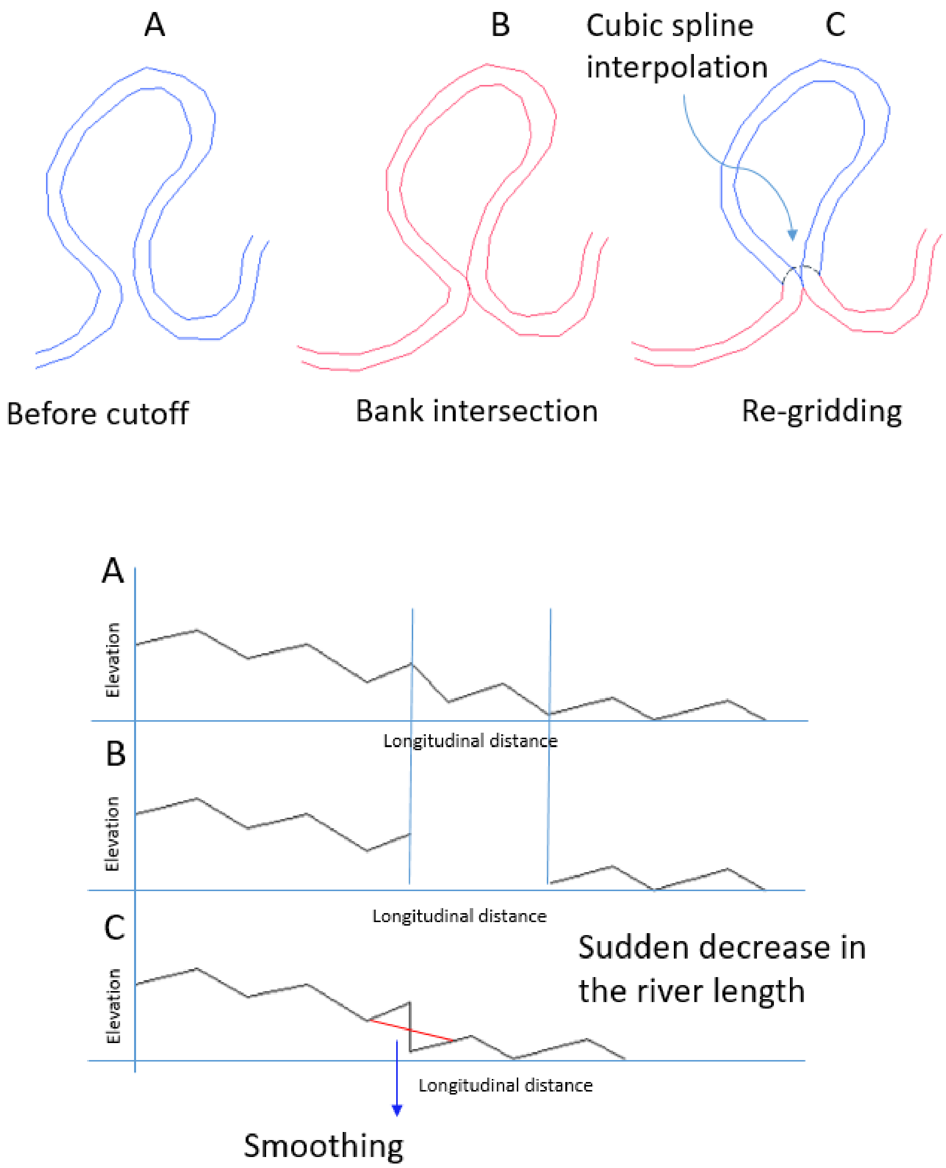

Figure 4.1 Treatment of planform evolution and changes in the bed elevation profile in the program A: Before cutoff, B: At the moment of bank intersection and C: Re-gridding.

In order to ensure a smooth transition between the bed elevations, the old bed topography was connected through a straight line Figure 4.1 Treatment of planform evolution and changes in the bed elevation profile in the program A: Before cutoff, B: At the moment of bank intersection and C: Re-gridding.. The model stops bed deformation for a period of time to allow the flow to stabilize in the new topography (straight line) and then continue with the numerical calculations. Finally, Figure 4.2 shows a resume of the followed methodology and how all the components are integrated to obtain the results.

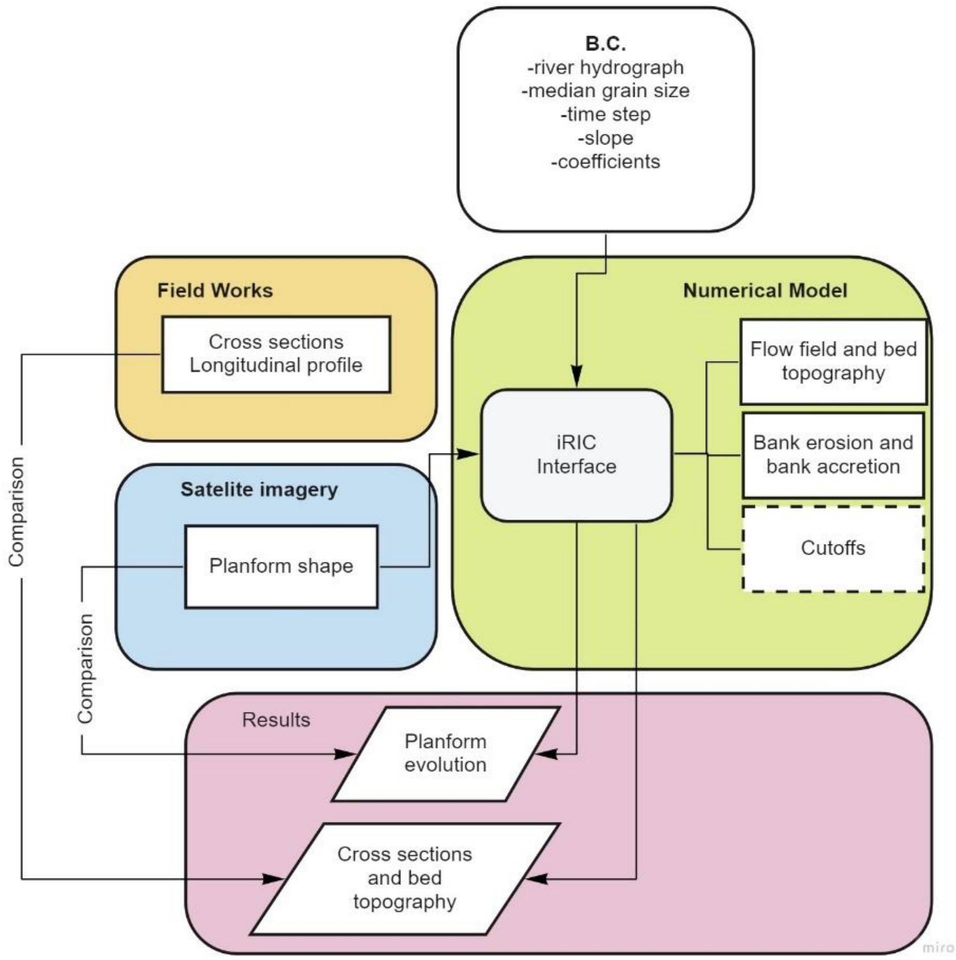

Figure 4.2: Diagram that shows the workflow of the numerical simulation. The data from the satellite imagery is used as initial planform shape. The results of the numerical simulation; planform shape, cross sections and bed topography are used for comparison with the results of the numerical model.

4.2.4 Model settings

The cases shown here try to test the ability of the model to reproduce and predict trends in meander migration in different locations of the Ichilo River.

The first case (C1) deals with long term migration trends in the upstream part of the Ichilo River. The initial planimetric configuration of the river was obtained from a satellite imagery of the river in the year 2006. This location was selected because three cutoffs were observed from 2006 to 2015. As we could not reach this area during the field trips only the satellite imagery provides us with the information for this part of the river. The study reach is 40 kilometers long of a freely meandering part of the Ichilo River, which includes around 16 meander bends of different sizes and shapes. The river channel flows in a dense forest, and to our understanding bank protection works have not been implemented. However, the use of land has changed drastically in the last 30 years with an increase of agricultural land around the river bends.

The second case (C2) deals with the ability of the model to predict planimetric changes. The initial planform shape of the channel was also derived from satellite imagery starting in the year 1988. The river with starts with the planform shape of the Ichilo River upstream of the confluence with the Sajta river and extends along 33 kilometres, which includes 12 meander bends. The initial planform shape is digitized from a satellite imagery and points from the left and right banks are extracted. The initial bed configuration of the river is set constant with a slope=0.004 which is the current average slope in Ichilo River that was obtained during the bathymetric surveys.A second simulation (C2-b) was performed starting in year 2018 to see the further development of a cutoff in the river given the modifications to the planform configuration in 1997.The final case (C3) investigates what would have happened if the intervention works of 1997 (Peters, 1998) were not performed in the Ichilo River. Table 3 summarizes the parameters used in the simulations.

Table 3: Parameters used in the numerical simulations

Parameter	**Unit**	**Case 1**	**Case 2**	**Case 3**
Grain size d50	(mm)	0.1		
Downstream water level		Uniform		
Grid size		10x180	10x180	10x180
Time step	(s)	1		
Simulation time	Years	25	25	40
Initial width (w_0)	(m)	130	200	215
Initial planform		2006	2018	1994
Minimum water depth treated as filled	m	0.2		
Time required to be excluded from the computational region (T_{land})	s	3600		
Bank erosion				
Non-Cohesive bank erosion factor		3		
Bank accretion				
Magnification factor of accumulation	-	3		
Minimum width ratio to the initial width	-	0.7	0.9	0.9
Time required for one mesh deposition	3	3600		

In all the cases we used the hydrograph of the Ichilo River from the gauge station of Puerto Villarroel. Water levels were transformed into discharge using a rating curve calculated by (Atahuichi Ramos, 2019) for the Ichilo River. A periodic boundary condition was imposed in all the simulations. The values for erosion and deposition rates were chosen according to the characteristics of the Ichilo River and to match the river planform evolution. The initial grid of the river was created using the extracted points of the banks from the satellite imagery and the shape of the river is smoothed using and interpolation technique, so the initial shape has a rather smooth shape with a uniform width.

4.3 RESULTS

4.3.1 Case 1

Planform evolution

The predicted planimetric evolution is shown in Figure 4.4. A cluster of three cutoffs were observed in the satellite imagery in years 2007, 2009 and 2015. The predicted location of the cutoffs and the area of the oxbow lakes formed agree well with the observations in the satellite imagery, with the exception of the cutoff of 2009. In this part, the river could have taken two possible paths to make the cutoff, upstream (full line) or downstream (dashed line). The satellite imagery shows that the development occurs in the upstream part but in the simulations the river took the downstream path, creating an oxbow lake with a larger area as shown in Figure 4.4-2009 and in Figure 4.3. In general, we observed that the model underestimated the areas abandoned by the channel as illustrated in Figure 4.3. The order in which the cutoffs developed starting in the middle, then downstream and finally upstream show that cutoffs may affect the planform geometry upstream and downstream of where they occur.

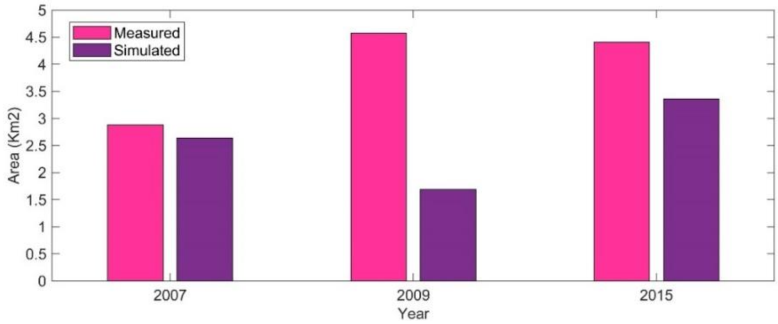

Figure 4.3: Comparison of the areas of the oxbow lakes formed during the cutoffs for Case 1.

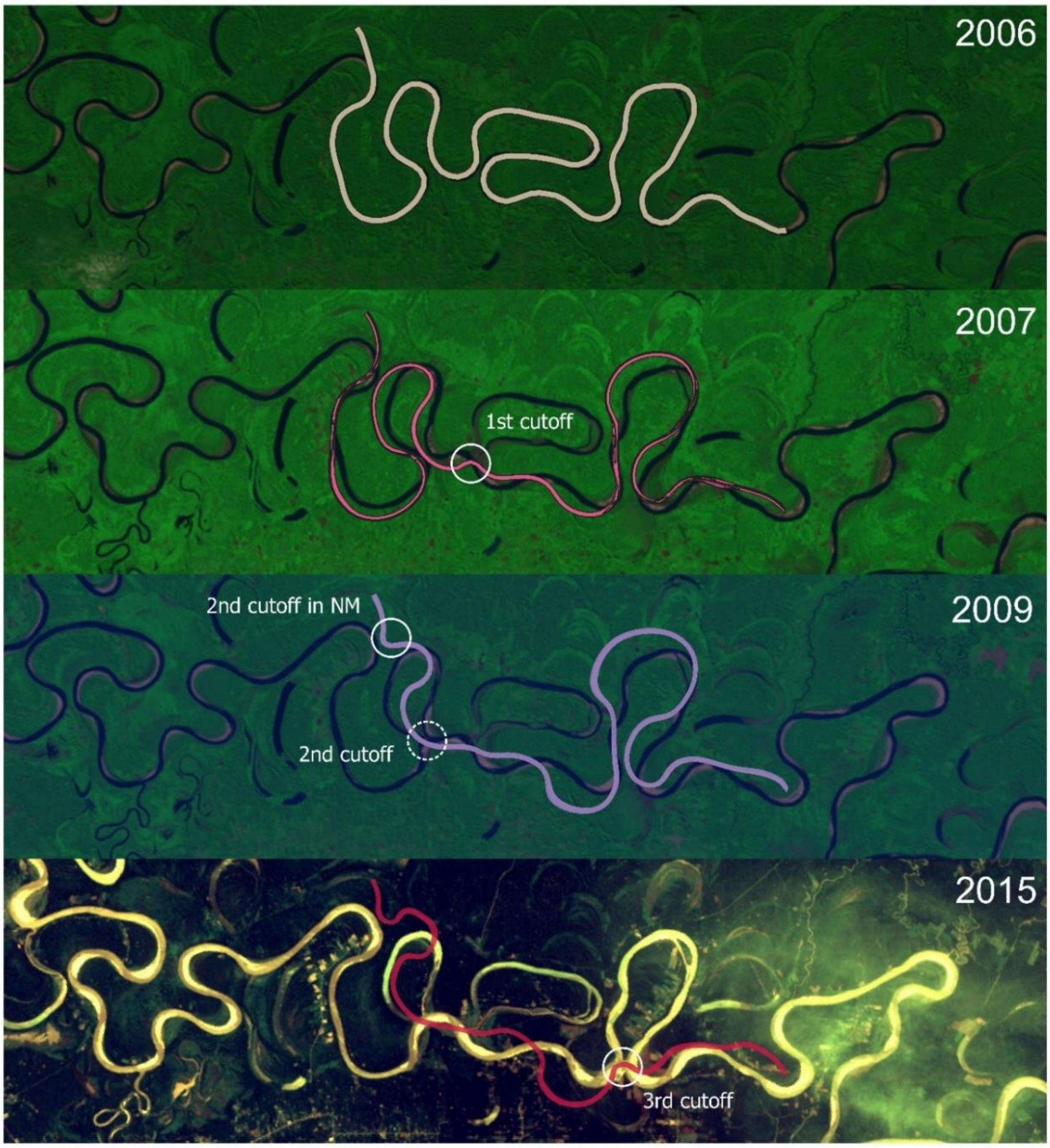

Figure 4.4: Observed vs computed planform shape of Ichilo River for Case 1. For the year 2009, the circles with a full line show the location of the cutoff in the numerical model while the circle with a dashed line shows the location where it was actually observed.

Water depths

The computer water depths are shown in Figure 4.5. As the river water levels vary along time they affect water depths calculations and bed development as well. In general water depths are deeper in the outer banks and shallower in the inner banks of the bends. In the model, as accretion processes depend on the water depths, different regions accrete at different times which generates changes in the channel width.

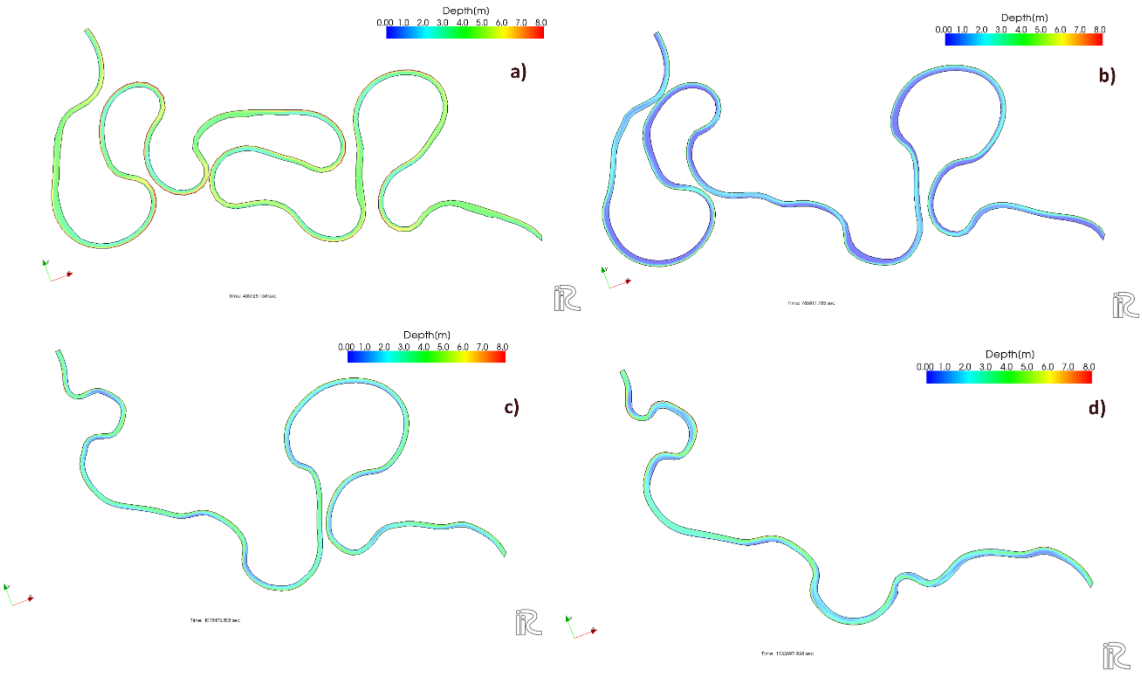

Figure 4.5: Computed waters depths for Case 1 (year 1994)

4.3.2 Case 2

Planform evolution

Figure 4.6 below shows the predicted river planimetric evolution for Case 2. Three cutoffs were observed along the channel during the simulated period. In this case, I compare the observed bed topography obtained during the bathymetric surveys for the initial stage of the model. Chute cutoffs were not taken into account as the model features only allow neck cutoffs to be simulated.

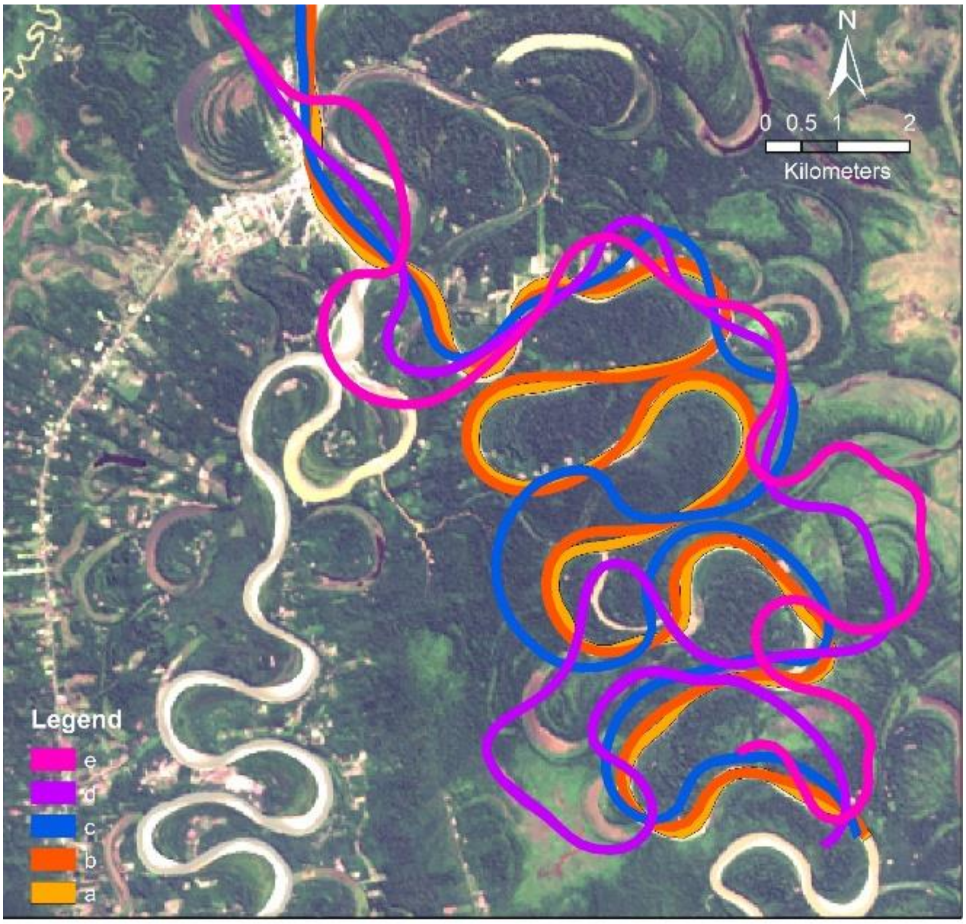

Figure 4.6: Background: study area in 2018 from a Landsat image. The letters (a) to (e) show the channel paths at different times, where (a) correspond to the initial channel shape of the river in 2018 and (e) the final shape at the end of the simulations.

Water depths and cross sections or water levels

Water depths are presented in Figure 4.7. The water depth variation is similar to the one of Case1, where the outer bends of the meanders were found to have deeper water depths and inner banks shallower water depths.

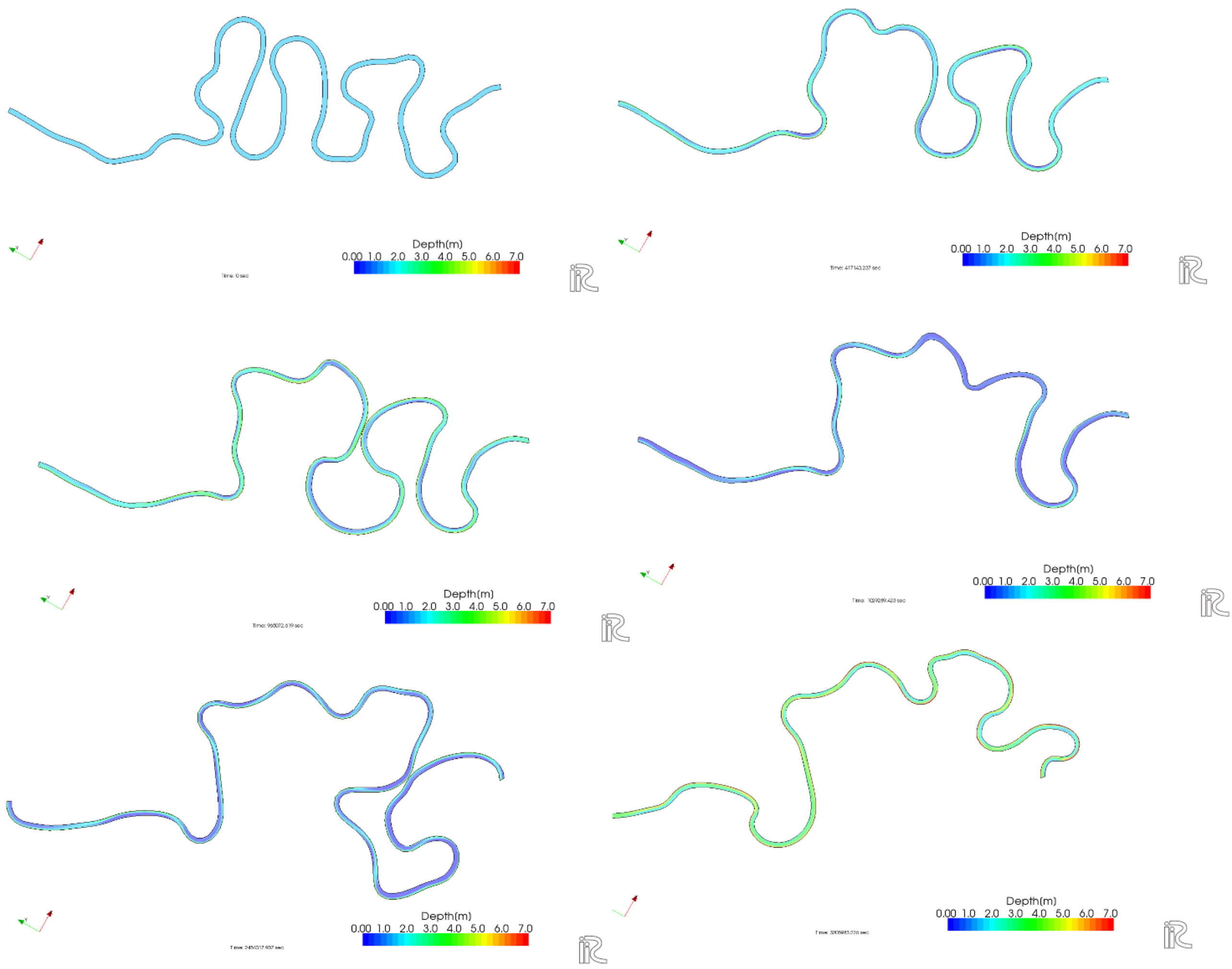

Figure 4.7: Computed water depths for Case 2 (year 2018)

4.3.3 Case 3

Planform evolution

The planimetric changes of this case are shown in Figure 4.9. Although validation is impossible since this is a hypothetical case, the computed trends agree with the planform changes observed until the development of the first cutoff. After that, the model was left to run to observe further changes in the planform. In the simulations, the 1st cutoff occurred near the location where the cutoff was expected to occur (Peters, 1998). As a consequence, the area where the port is located was abandoned by the river as predicted by Peters (1998). Differences between the predicted and observe planform may be explained by the presence of non-erodible banks in the river in the area of the port. Several protection works have been constructed to avoid erosion and flooding, using different materials such as concrete and gabions as it can be observed in Figure 4.8. The model assumes a heterogeneous floodplain and this effect is not considered.

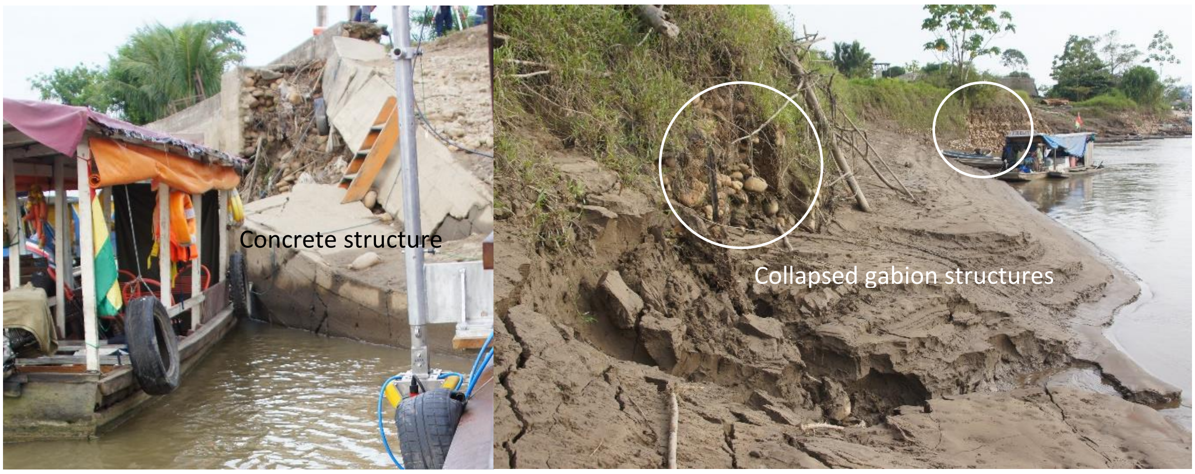

Figure 4.8: Bank protection measures in the Ichilo River. Left: Concrete structure, right: gabions.

Furthermore, during the calibration different degrees of smoothing after bank accretion and bank erosion were tested along the simulations. Figure 4.9 shows the comparison of the numerical simulations with exact same values but the number of times of the smoothing varies from 0 (left) to 3 (right). The difference in the planforms is very clear, with higher smoothing numbers small bends tend to disappear from the planform and meanders with larger wavelengths developed. Although the bends are smoother, the shapes are unrealistic with meanders that grew with distorted shapes until they reach a large size compared to the planform observed in the satellite imagery.

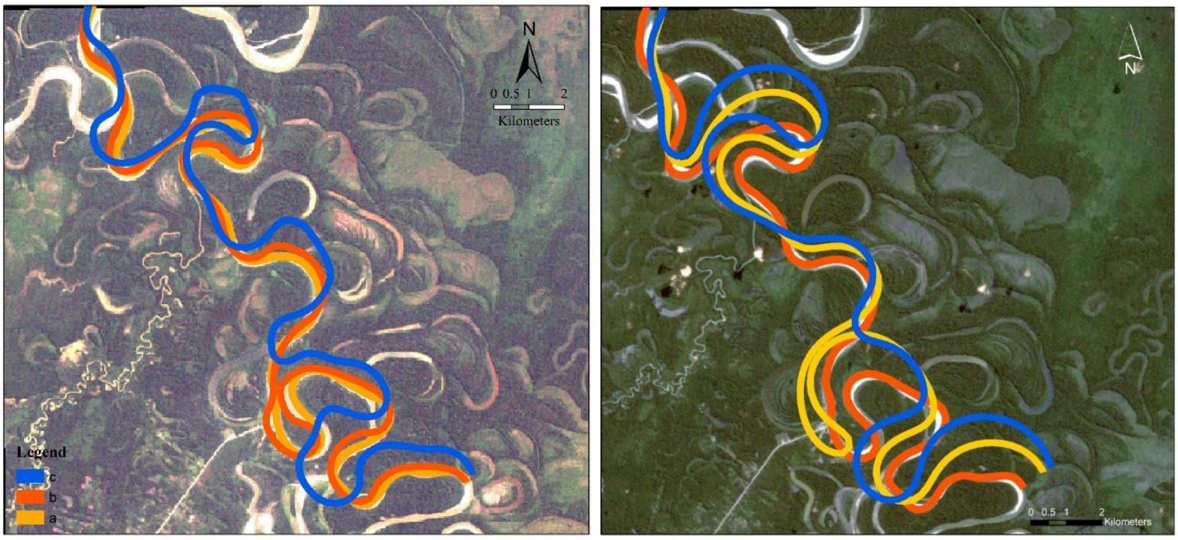

Figure 4.9: Hypothetical case C3 where the Ichilo River is left without the human interventions of 1997.The orange channel corresponds to the planform of Ichilo River in the year 1994, yellow line the planform evolution just at the moment of the 1st cutoff and the blue line the final form at the end of the simulation. On the left, the results without smoothing after bank accumulation and bank erosion, and on the right the results where the smoothing is performed 3 times.

Water depths and cross sections or water levels

Similar to previous cases, the water depth where deeper in the outer bends and shallower in the inner bends Figure 4.10.

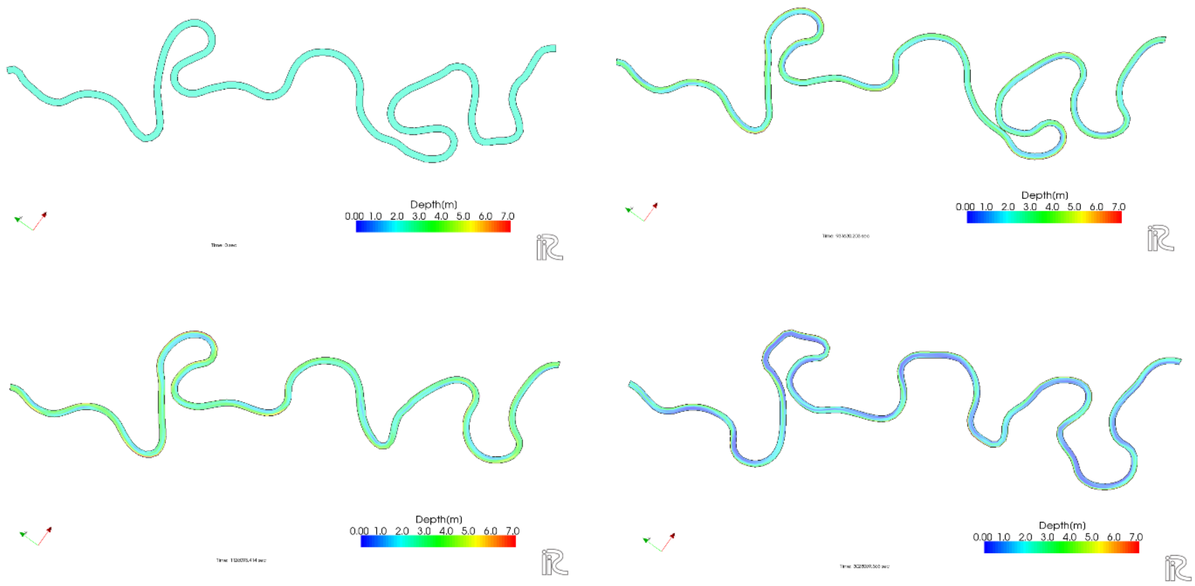

Figure 4.10: Computed water depths for Case 3 (year 1994)

4.4 DISCUSSION

In this study we explored the possibility of improving the numerical model of (Asahi *et al.*, 2013) in order to simulate the trends on meander migration at the real scale of a river of the Amazon basin. Our results show that the improved model was able to reproduce the meander migration trends of the Ichilo River, including the occurrence of neck cutoffs. The model results agree with the planform shapes obtained from remote sensing data and with the bathymetric surveys performed on 2019 in terms of cross sections and riverbed topography.

Our three cases of simulations have shown the ability of the model to reproduce different shapes of the Ichilo River in different parts of the reach. The following effects on the planform shape are discussed: Initial planform shape, water levels effect, the effect of smoothing and regridding, and the width variation.

Width variation

The relatively recent inclusion of the width variation in meander migration models has meant a huge improvement for the numerical simulations, which allowed to study their effect consequences in the bed topography and the migration rates of meandering rivers (Crosato, 2008). Crosato (2008) (and recently Monegaglia et al. 2019) stated that numerical models of meander migration lose their sediment transport capacity as the meandering bends tend to grow given the assumption that the slope decreases as the channel elongates, which led to unrealistic narrow channels. This problem was approached this problem by introducing a minimum width ratio which related the initial width with the predicted width. In this study, the results showed that if the minimum width vary less than 30% of the initial width, the planform evolution developed more realistically. This is in accordance with the results of Moneglaglia et al. (2019) who stated that sand bend rivers do not exhibit width changes larger than 30%. Moreover, the satellite imagery has shown that the average annual width of the Ichilo River has changed from 120 to 190 m. As a result, the channel regulates its own slope by the occurrence of cutoffs as it was shown in the results of the simulations of the Ichilo River.

Cutoffs

For long term simulations in meandering rivers like the Ichilo, dealing with neck cutoffs is unavoidable. The satellite imagery has shown the development of 10 neck cutoffs in the Ichilo River since year 1988. The cutoff development and their different stages like the increase of the slope, which is the initial dominant morphodynamics response to cutoffs in alluvial rivers, (Schwenk and Foufoula-Georgiou, 2016) was simulated by the model together with the differences that arise during the occurrence of cutoffs in the bed profile. The cutoff occurrence was dealt by using a smoothing curve to help the transition between bed and bank profiles. The initial stage of the neck cutoff, the intersection of the bends, was well reproduced by the model in terms of location. The further planimetric shape of the cutoff depended on the sections before and after the cutoff which was connected through a spline curve and the new bed was connected by a smoothing line giving some time to the model to allow the changes to take place and help the model to stabilize and then continue with the bed evolution.

At certain point during the cutoff development, as the distance in the neck reduces the exchange of water between the channels starts. This exchange will depend on the type of material observed in the banks. In the experiments of Li et al. (2019), it was observed that water flow in the banks accelerate the occurrence of cutoffs (Li, Wu and Gao, 2019). However, that effect is not considered in the model.

Water level variation

The effect of the water level variation (in here water levels are extrapolated to the variation of the discharge) on the planform evolution depends on the magnitude and duration of the high and low flow discharges (Asahi et al., 2013). Assuming that a single value of the discharge can reproduce the effects of the full river flow regime would be unrealistic (Vargas Luna, 2016).

This effect is particularly important in the case of the Ichilo River due to the water level variation observed. In the model, water levels control the narrowing and widening of the river width given that the model considers accretion during the low discharge and erosion during the high discharges.

Limitations

Limitations of the methodology are discussed in the following lines. Regarding the model, one of the main limitation is the simplification of the floodplain as a homogeneous material. Second, the model does not consider the effects of flooding state of the river. The analysed data suggested that the meandering migration rates are partially correlated with the number of days in which the bank was flooded, which may lead to underestimations in the migration rates when they are not considered. The simulated area did not include tributaries. However, the recent reactivation of the meandering migration triggered by a cutoff occurred in Sajta river shows the existing connection between this two rivers (Ichilo and Sajta) and future changes in the may have to consider the tributary to guarantee the port accessibility. The recent collapse of a part of the port shows the importance of studding this topic and showing the possible reaction of the river to different changes in the environment.

We have to notice that the water level variation may be influenced by changes in the bed elevation (sediment input and output) as the river bathymetry changes every flooding season in general, hence statistically high water level may not correspond high discharge every time (Shampa et al); and the discharge from Sajta river.

However, the numerical simulations in here should be seen as a virtual channel that is based as much as possible in the Ichilo River and not try to reproduce the shape of the Ichilo exactly given the lack of information about the subsoil, but rather to reproduce the meander migration trends.

Effect of smoothing and re-gridding

When dealing with numerical simulations of meandering channels, smoothing techniques have demonstrated to be very useful and often used to reduced errors but they may affect the planform configuration of the river as observed by Crosato (2006). In here different results were observed when smoothing techniques were used for bank erosion and bank accretion lines. We noticed that small bends were removed from the simulations and that river width was kept almost constant as a result of the smoothing techniques. In the computational tests, spline interpolations were used after bank erosion and bank accretion. More realistic planform shapes and widths were observed when the smoothing was not performed.

Finally, we discuss the meaning of the results by integrating the three approaches (Chapter 2 and Chapter 3). It is clear that the Ichilo River is and has been changing during the studied period and further changes are expected to occur very soon. The planform configurations in the Ichilo River is the result of a heterogeneous floodplain that is defined by multiple factors such as the floodplain material, vegetation, and presence of oxbow lakes, which affect meander migration rates (Monegaglia and Tubino, 2019). The data collected and the remote sensing analysis together with the SfM suggest that meandering cutoffs are expected to occur in the Ichilo River soon in the area near the confluence, called #F1 in Chapter 2. I suggest this because the distance in the neck has been decreasing at a faster rate. In thirty years has decrease a 75% of the initial distance while in section two (#F2) has only decreased 50% of the initial distance which can be explained by the floodplain heterogeneity. Our last measurement (from the orthophotos obtained in May) suggest that the river in section one has a distance of less than 100 m. As this distance, decreases intra meandering flow in the neck of the cut off may increase from one side to the other.

As for the floodplain, there are parts in Ichilo River that are more stable that other due to geological reasons (Peters, 1998). The area corresponding to the region between the port and the intersection of with Sajta rivers has maintained its original planform shape since 1988 with minor modifications (Slight increase in the width), while other parts are experiencing constant erosion especially along the bends. The planform shape evolution in the model depends on the initial shape of the river, particularly in the short term because the initial shape intrinsically is the result of the floodplain heterogeneity of the river (Monegaglia and Tubino, 2019). The unknown characteristics of the subsoil may explain the differences between the model and the simulations, where areas of the river stay in the river without no apparent changes while other areas experience high meandering migration rates, the soil variability is a factor that control meander migration rates as was demonstrated by (D. Motta *et al.*, 2012).

Future works should include the intra-meandering flow, therefore, more field works are necessary in order to improve numerical models. As for the numerical simulations have shown that the results fall inside the river corridor that was calculated from the river using the 30 years' satellite imagery available. This study shows the ability of the model to reproduce planform shapes using a combined approach using satellite imagery and field works to reproducing long term trends of migration in the Ichilo River where the fast land scape changes seem to be of high importance for the inhabitants of the city of Puerto Villarroel.

4.5 CONCLUSIONS

In here we move a is a step forward to numerical simulations of meandering rivers. In here, a numerical model that simulates the trends of meander migration is presented and the first attempt to apply the model to a large spatial scale. The development of neck cutoffs is captured by the model. The model therefore has managed to reproduce the results in terms of the profile and cross sections regardless its limitations and move us a step forward in answering the question that was set in the introduction. (How rivers will respond to natural/ human-induced perturbations?).

The Ichilo River has remained relatively free of human influence. However, as years passed by and the population has growth, sporadic interventions have been made in the area near the port. In order to investigate this problems, numerical simulations may be a potent tool to decide the best course of action and their consequences in meandering rivers as the Ichilo. The evolution of Ichilo River should be carefully monitored given that the city is located just near the river and the port and the city may be endangered by future changes in the path as it was in year 1996 and recently last year with the collapse of the platform of the port. We believe that a neck cutoff will develop in the near future and close to the city of Puerto Villarroel presenting further changes to the ever-changing landscape of Puerto Villarroel.

CHAPTER 5: SUMMARY AND FUTURE WORK

The Amazon basin is the place of many active meandering rivers. Meandering rivers planform and the changes that they experience depend on many factors such as climate, human interactions. Most of the rivers that have been studied in the Amazon basin are large rivers, but rivers in the southern Amazon basin exhibit different characteristics such as short inundation periods, high fluctuation in the water levels when compared to the rivers that are located downstream. The lack of information about this meandering rivers still rises many questions that are waiting for an answer. What are the controls on meander migration in this rivers? How to collect information in this rivers? and can we reproduce the trends about meander migration in the short to medium term?

I chose a meandering river in the southern part of Bolivia with the characteristics mentioned above: The Ichilo River. Topographic surveys in the river were performed by using a combined methodology of SfM and a Multibeam Echosounder (MBES). The collected data allowed us to explore the bathymetric data of the Ichilo River and the shape of the banks at a high quality. The study of this river was complemented with a spatiotemporal analysis to understand the river from an integral point of view that considers the past history of the river with the available tools.

This analysis suggest that neck cutoffs play an important role in the planform configuration of the Ichilo River. High events of precipitation may explain the increased migration rates observed after 2007, and the event of 2014 may be related with the occurrence of cutoffs observed after that period.

Furthermore, I present a numerical model that captures important characteristics that have been observed from the results of the spatiotemporal analysis and the field works to reproduce the trends of meander migrations. The model considers the following characteristics:

i) Planform shape evolution after cutoff
ii) Profile change due to cutoff
iii) Inner bank accretion and outer migration as a result of the water level variation

The model is able to reproduce the trends of meander migration in terms of the planform shape evolution, location of cutoffs and area of abandoned oxbow lakes, and the results presented here is one of the first that show meandering evolution in a river of the Bolivian Amazon basin.

The purposed model can be applied to assess the planimetric changes of meandering rivers at the scale of the Ichilo River. This study has also found that future planimetric planform changes are very likely to occur in the river in the near future due to the menace of future cutoff (#F1).

Future work, should consider the extension of current modeling framework. It is assumed at this stage that the floodplain is homogeneous in time and space. It has been previous demonstrated the effect of bank heterogeneity has effects on the planform shape of meanders and therefore should be included in the analysis. Also, the effect of the ground water level should be taken into account, especially in places like the Ichilo River where water levels show high variation in a relative short period of time. Water level variations may affect the groundwater levels and at the same time decrease the bank stability, further studies are necessary on this matter, specifically field works.

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APPENDIX

1: Ground Control Points coordinates and coordinates obtained from the DEM after the correction. The points in blue are used to correct the DEM and the rest to calculate errors.

	RTK - Base in BM-3			SfM photogrammetry (DEM)		
GCPs	East	North	Altitude	X_Ev	Y_Ev	Z_DSM
PD-01	309188.178	8137470.19	208.153	309188.162	8137470.18	208.159
PD-02	309036.681	8137408.06	211.766	309036.694	8137408.04	211.735
PD-03	309202.929	8137324.21	208.147	309202.94	8137324.21	208.271
PD-04	309045.804	8137223.92	211.889	309045.804	8137223.92	211.906
PD-05	309044.504	8137168.23	209.187	309044.504	8137168.23	209.264
PD-06	309044.215	8137097.18	212.268	309044.215	8137097.18	212.286
PD-07	309070.487	8137052.55	208.858	309070.487	8137052.55	208.907
PD-08	309318.548	8137125.58	208.049	309318.548	8137125.58	208.104
PD-09	309102.292	8136995.83	210.114	309102.292	8136995.83	210.136
PD-10	309110.287	8136966.38	211.288	309110.287	8136966.38	211.326
PD-11	309135.42	8136915.26	208.33	309135.42	8136915.26	208.466
PD-12	309130.425	8136900.71	212.216	309130.425	8136900.71	212.206
PD-13	309161.219	8136864.79	211.342	309161.219	8136864.79	211.402
PD-14	309394.359	8137023.37	207.803	309394.326	8137023.42	207.874
PD-15	309200.121	8136816.97	211.19	309200.121	8136816.97	211.203
PD-16	309245.007	8136767.31	210.112	309245.007	8136767.31	210.115
PD-17	309257.8	8136743.17	212.215	309257.8	8136743.17	212.225
PD-18	309299.153	8136708.14	209.512	309299.153	8136708.14	209.518
PD-19	309501.062	8136904.41	207.971	309501.062	8136904.41	207.965
PD-20	309327.217	8136677.96	210.153	309327.217	8136677.96	210.18
PD-21	309362.434	8136631.84	212.076	309362.434	8136631.84	212.08
PD-22	309390.853	8136616.52	208.29	309390.853	8136616.52	208.324
PD-23	309409.652	8136595.11	209.223	309409.652	8136595.11	209.189
PD-24	309763.034	8136530.97	210.194	309763.034	8136530.97	210.214
PD-25	309811.526	8136482.95	211.162	309811.526	8136482.95	211.133
PD-26	309765.875	8136472.54	208.666	309765.875	8136472.54	208.719
PD-27	309644.515	8136235.19	208.554	309644.515	8136235.19	208.685
PD-28	309771.808	8136225.24	208.052	309771.808	8136225.24	208.058
PD-29	309926.446	8136184.63	211.057	309926.446	8136184.63	211.045
PD-30	310102.677	8136177.96	207.974	310102.677	8136177.96	207.992
PD-31	310184.727	8136312.09	208.135	310184.727	8136312.09	208.195
PD-32	310301.866	8136133.9	208.45	310301.866	8136133.9	208.48

PD-33	310549.266	8136062.03	208.144	310549.266	8136062.03	208.145
PD-34	310728.524	8136077.43	208.976	310728.524	8136077.43	208.998
PD-35	310768.519	8135656.44	208.222	310768.519	8135656.44	208.25
PD-36	310959.48	8135481.84	208.804	310959.48	8135481.84	208.838
PD-37	311007.351	8135135.18	208.908	311007.351	8135135.18	208.894
PD-38	311052.717	8135002.4	209.185	311052.717	8135002.4	209.283
PD-39	311331.31	8134588.23	208.805	311331.31	8134588.23	208.94
PD-40	311764.339	8135085.67	208.909	311764.339	8135085.67	208.837
PD-41	311929.551	8135048.82	208.729	311929.551	8135048.82	208.775
PD-42	311889.678	8135307.2	208.435	311889.678	8135307.2	208.446
PD-43	311726.451	8135464.29	209.476	311726.451	8135464.29	209.451
PB_0	309032.735	8137409.23	212.242	309032.735	8137409.23	212.331

2. Errors calculated for the coordinates x, y and z.

Errors					
UAV Points	Error X (m)	Error Y (m)	Dist. XY (m)	Error Z (m)	Error Abs Z (m)
PD-01	0.02	0.01	0.02	-0.01	0.01
PD-02	0.01	0.02	0.02	0.03	0.03
PD-03	0.01	0.01	0.01	-0.12	0.12
PD-04	0.00	0.00	0.00	-0.02	0.02
PD-05	0.00	0.00	0.00	-0.08	0.08
PD-06	0.00	0.00	0.00	-0.02	0.02
PD-07	0.00	0.00	0.00	-0.05	0.05
PD-08	0.00	0.00	0.00	-0.06	0.06
PD-09	0.00	0.00	0.00	-0.02	0.02
PD-10	0.00	0.00	0.00	-0.04	0.04
PD-11	0.00	0.00	0.00	-0.14	0.14
PD-12	0.00	0.00	0.00	0.01	0.01
PD-13	0.00	0.00	0.00	-0.06	0.06
PD-14	0.03	0.05	0.06	-0.07	0.07
PD-15	0.00	0.00	0.00	-0.01	0.01
PD-16	0.00	0.00	0.00	0.00	0.00
PD-17	0.00	0.00	0.00	-0.01	0.01
PD-18	0.00	0.00	0.00	-0.01	0.01
PD-19	0.00	0.00	0.00	0.01	0.01
PD-20	0.00	0.00	0.00	-0.03	0.03
PD-21	0.00	0.00	0.00	0.00	0.00
PD-22	0.00	0.00	0.00	-0.03	0.03
PD-23	0.00	0.00	0.00	0.03	0.03
PD-24	0.00	0.00	0.00	-0.02	0.02
PD-25	0.00	0.00	0.00	0.03	0.03
PD-26	0.00	0.00	0.00	-0.05	0.05
PD-27	0.00	0.00	0.00	-0.13	0.13
PD-28	0.00	0.00	0.00	-0.01	0.01
PD-29	0.00	0.00	0.00	0.01	0.01
PD-30	0.00	0.00	0.00	-0.02	0.02
PD-31	0.00	0.00	0.00	-0.06	0.06
PD-32	0.00	0.00	0.00	-0.03	0.03
PD-33	0.00	0.00	0.00	0.00	0.00
PD-34	0.00	0.00	0.00	-0.02	0.02

PD-35	0.00	0.00	0.00	-0.03	0.03
PD-36	0.00	0.00	0.00	-0.03	0.03
PD-37	0.00	0.00	0.00	0.01	0.01
PD-38	0.00	0.00	0.00	-0.10	0.10
PD-39	0.00	0.00	0.00	-0.13	0.13
PD-40	0.00	0.00	0.00	0.07	0.07
PD-41	0.00	0.00	0.00	-0.05	0.05
PD-42	0.00	0.00	0.00	-0.01	0.01
PD-43	0.00	0.00	0.00	0.03	0.03
PB_0	0.00	0.00	0.00	-0.09	0.09
Average	**0.00**	**0.00**	**0.00**	**-0.03**	**0.04**
Standard Deviation	**0.01**	**0.01**	**0.01**	**0.05**	**0.04**