MORPHODYNAMICS OF A SMALL MEANDERING RIVER IN THE AMAZON BASIN FROM LANDSAT AND UAV

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ABSTRACT

This study analyzes the planform evolution of a meandering river and its tributary, the Ichilo and the Sajta rivers, located in southern part of the Amazon basin in the city of Cochabamba, Bolivia by using Landsat imagery and the processing tool RivMAP to obtain meandering metrics. The analysis is performed along 150 kilometers of the Ichilo river from years 1988 to 2018. We observe the development of cutoffs, migration rates, and bank erosion and accretion processes. Furthermore, river morphology dynamics were mapped using images acquired with an unmanned aerial vehicle (UAV). The data obtained from the UAV was processed and orthophotomosaics were created.

The results for this study helps us improve the understanding of the morphodynamics of the Ichilo River, showing that neck cutoffs are main controls in the planform configuration of the river. Our study suggest that ENSO events may have affected migration rates in Ichilo River in the year 2008. Furthermore, high water level variation and the groundwater levels may have an effect on bank erosion processes. Two possible scenarios where cutoffs are expected to occur were identified. These scenarios present further changes to the ever evolving landscape of the Ichilo river.

Keywords: Ichilo River, bank erosion, meander migration, neck cutoffs, water level variation

1. INTRODUCTION

The complex planform shape and the river dynamics of actively meandering rivers of the Amazon basin have been studied using different techniques such as; remote sensing (Gomes et al., 2018; Schwenk et al., 2017), field measurements (Gautier et al., 2010), and numerical modelling (Schwenk et al., 2015). These studies have helped us to improve the understanding of different variables that control the planform dynamics of these meandering rivers, such as the effects of the human activity, geological constrains, climate change, deforestation and sediment supply (Horton et al., 2017; Lombardo, 2016).
The Amazon river network is composed by a large number of tributaries, and most of them are considered to be 'small rivers' as referred by Lombardo (2016). Nevertheless, most of the studies are concentrated on the Amazon main tributaries. For this reason, earlier studies (Lombardo, 2016) have pointed out the necessity to study further about these small meandering rivers.
Small rivers located in the southern upstream Amazon, like the Ichilo and the Sajta rivers, have unique characteristics such as flooding periods of very short duration compared to the ones located downstream (Rejas, 2018) (e.g. the Mamoré and Beni Rivers), and highly variable water levels (Figure 1).

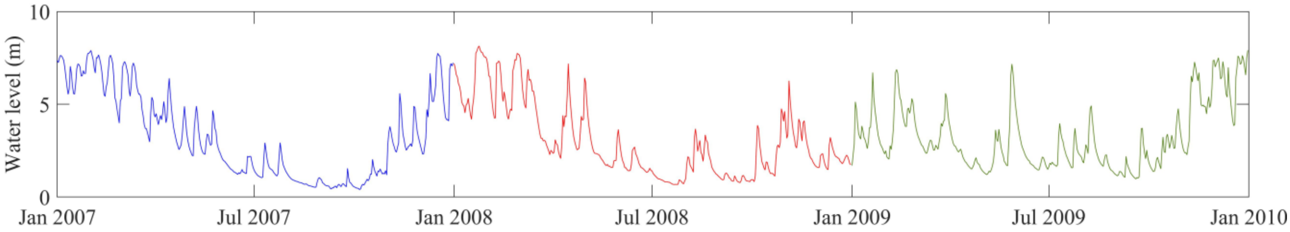

Figure 1. Water level variation in Ichilo River from January 2007 to January 2010 from the Puerto Villarroel station. Source: Semena (Servicio de Mejoramiento de la Navegación Amazónica).

In this paper we focus on the Ichilo river, a small meandering river in the southern Bolivian Amazon basin and its tributary the Sajta river. We analyzed Landsat imagery using the Google Earth Engine (GEE) (Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, 2017) along 150 kilometers of the Ichilo river for a period of 30 years using annual bankfull masks in order to compute meander migration metrics. The analysis was performed qualitatively and quantitatively and field works complemented the Landsat imagery analysis giving us insights on bank erosion processes.

2. AREA OF STUDY

The area of study was identified through satellite imagery available in the Landsat catalogue (Landsat 5, 7 and 8) using the GEE. We covered an area of 46.7*45.4 square kilometers. The initial point of the analysis starts in the intersection of the Ichilo River with the Izozog River (upstream) and finishes downstream in the confluence of the Ichilo river with the Chimoré river, where it changes its name from Ichilo to Mamorecillo and continues flowing until it becomes the Mamoré River. In the upstream part, the river exhibit a braided and anabranching configuration but it changes to a meandering condition as the slope decreases downstream after leaving the Andes Mountains (Peters, 1998); and when the river approaches the city of Puerto Villarroel it is already a well-defined meandering river. Oxbow lakes, paleo channels and meandering scars from old paths of the Ichilo River can be appreciated along its floodplain showing its dynamic behavior.

3. METHODOLOGY

We searched for cloud-free satellite imagery from the Landsat catalogue for the period from 1988 to 2018 to perform the planimetric analysis. Each year, we selected an imagery that corresponded to the months with low flows (from June to October) as suggested by Schwenk et al. (2017). If a cloud-free imagery was not available in that period we searched for the whole year, until we found a representative image for that year. However, in some years the imagery was not available or the quality was poor; therefore, they were not included in the analysis (Table 1).

Table 1. Years that were not included in the analysis due to poor quality

	YEARS
ICHILO RIVER	2012, 2007, 2002, 2000,1997, 1992, 1990, 1989

After selecting the representative imagery, a classification was performed in the GEE by using a support vector machine (SVM) model. Each imagery was classified using three classifiers: water, sediment and vegetation. First, training data of known classes was collected (i.e. water, land, and vegetation) and then, the image was classified. The objective of this classification was to obtain a well-defined full channel centerline masks to analyze the planforms. The analysis of the planforms was made by using the River Morphodynamics from Analysis of Planforms (RivMAP) tool box (Schwenk et al., 2017), which allowed us to quantify river planform changes from the binary channel masks. The following information was obtained: centerlines, bank lines, river widths, migration rates, cutoffs, erosion and accretion areas. More details about the cleaning, classification and the RivMAP toolbox can be obtained from (Schwenk et al., 2017).

The analysis of the satellite imagery was complemented with two field surveys that were performed in February and May of 2019 with the objective to identify areas of bank erosion. High-resolution photos were taken using two unmanned aerial vehicles (UAVs): a DJI Phantom 4 and a DJI Mavic Pro. The imagery was analyzed and processed using the software Agisoft PhotoScan and orthophotos were obtained from the analysis.

4. RESULTS AND DISCUSSION

4.1. Meander migration

The centerline changes along thirty years (from 1988 to 2018) (Figure 2) illustrate the active behavior of the Ichilo river. This change is evident particularly when cutoffs occurred (cutoff #1 to #10). During the studied period, a total of thirteen cutoffs were identified. Neck cutoff was the prevalent cutoff mechanism with a total of ten events observed from which one of these neck cutoffs was the result of human intervention (Peters, 1998).The other three were identified as chute cutoffs. The areas abandoned by the river when a neck cutoff occurred are presented in Figure 2; where the largest area corresponds to the human-induced neck cutoff (cutoff #9) that occurred in January of 1997 (Peters, 1998).

Table 2. Area of river abandoned as result of neck cutoff.

Cutoff #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9***	**10**
AREA (KM^2)	0.8	0.4	3.4	2.6	1.7	1.1	2.5	2.2	4.7	1.7
YEAR	1991-1993	1991-1993	2014-2015	2007-2008	2008-2009	2014-2015	2009-2010	2009-2010	1997	1999-2001

***Human induced cutoff**

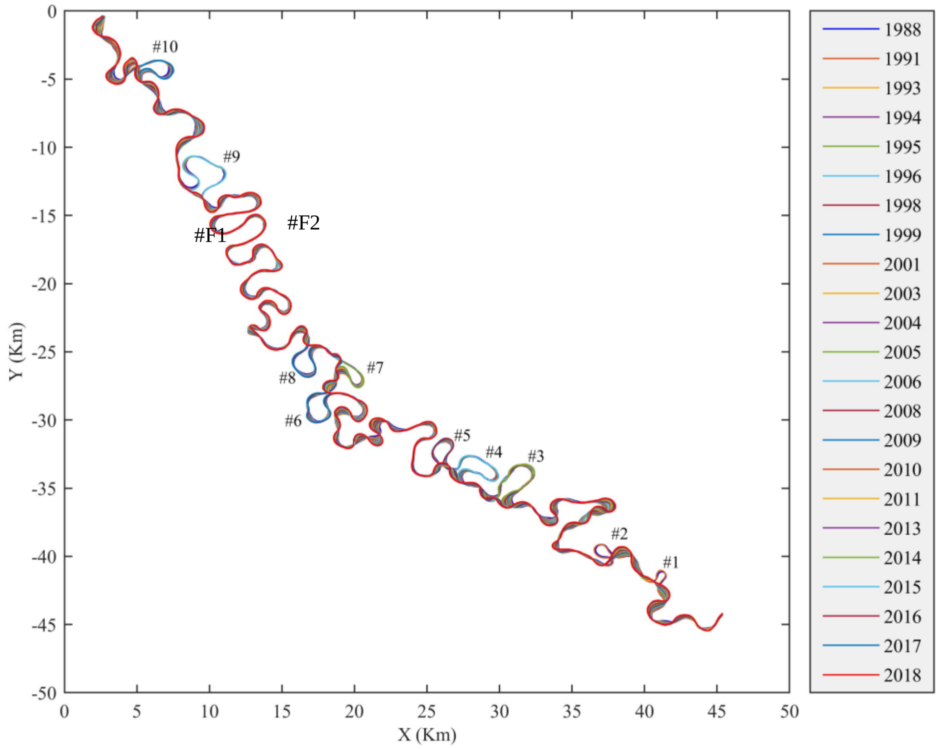

Figure 2. Centerlines migration of the Ichilo River from 1988 to 2018. The river flows from south to north. The location of neck cutoffs observed are marked in the map.

Examples of meandering mechanisms of the Ichilo and the Sajta River were identified in the satellite imagery and are presented in Figure 3. Figure 3a-b show the change of a group of meander loops in Sajta River where lateral expansion over a period of thirty years is observed. The development of a chute cutoff along eight years is shown in Figure 3c-d, where the abandoned path of the river re-connected with the main channel resulting in the said chute cutoff. A neck cutoff in the main tributary of the Ichilo river (Sajta River) is presented in Figure 3 e, f and g, and as a result, an oxbow lake has been formed (Figure 3e) as testimony of the dynamic nature of the river.

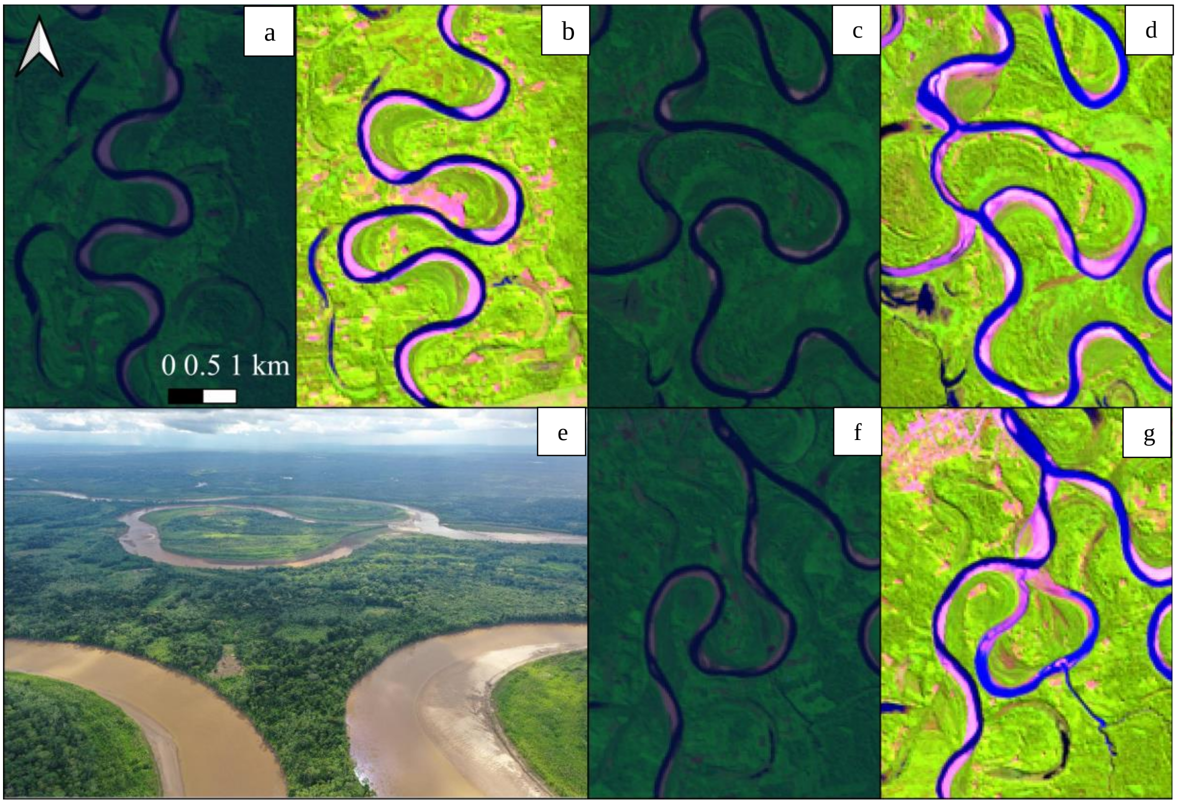

Figure 3. Migration mechanisms in the Ichilo River and its tributary the Sajta River. Lateral expansion 1988 (a) and 2019(b) in the Sajta River. Chute cutoff in the Ichilo River in 2011(c) and 2019 (d). Picture of neck cutoff on the Sajta river taken with drones during field trip on February, 2019 (e) and development of the neck cutoff from 2006 (f) to 2019 (g).

Annual average channel widths were calculated and are presented in Figure 4 where the average width of Ichilo river for the complete period was calculated to be 165.9 m. Although meandering rivers seem to have a constant width it is known that the river experience period of widening and narrowing which may depend on accretion and erosion rates (Schwenk et al., 2017).

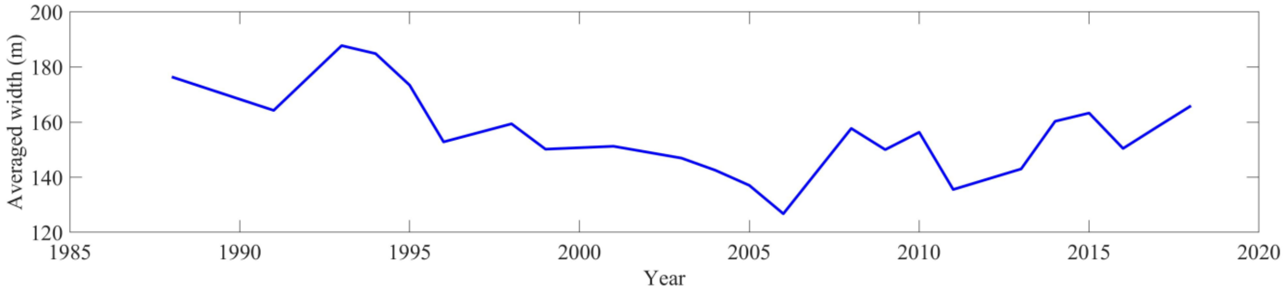

Figure 4. Annual average width variation in Ichilo River

Cumulated areas of accretion and erosion (Figure 5) shows no significant difference between accretion and erosion with a slight increase from the year 2005 in the eroded areas.

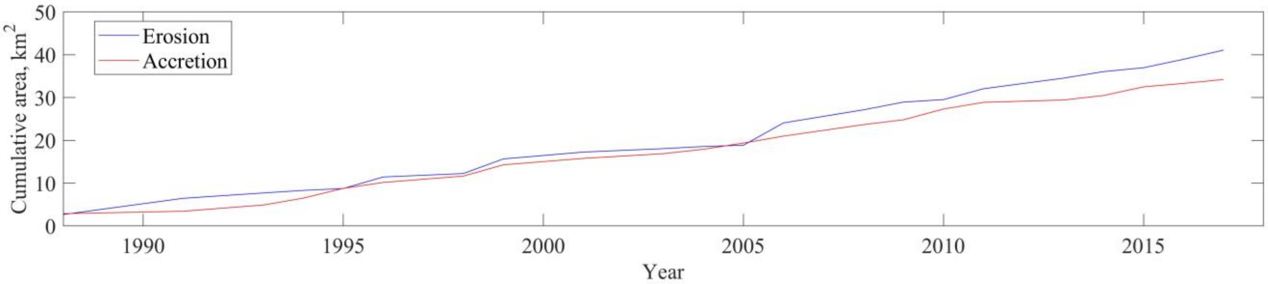

Figure 5. Cumulative erosion and accretion areas in Ichilo River

The reach averaged migration rate of the Ichilo river for the complete period was calculated to be 11.01 m/year with a peak that occurred in year 2008 (Figure 6). 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 Ichilo river remained five days flooded in January of 2008, with water levels over the bank level (>7.8 m), this event could explain the peak observed in (Figure 6). Furthermore, the maximum annual stage (S_{max}) was plotted against the migration rates (Figure 7) and the results showed a small to moderate correlation with the annual average migration rates (M_{rcl}) (R^2=0.22). Similar effect was observed by (Schwenk et al., 2017) in his analysis of the Uyacali River.

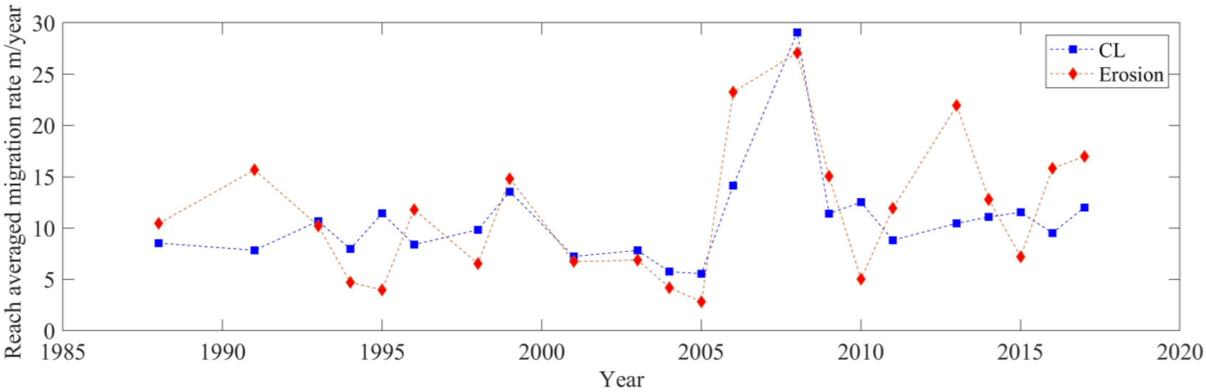

Figure 6. Reach average migration rate per year (red: based on centerline migration (CL), blue: based on erosion)

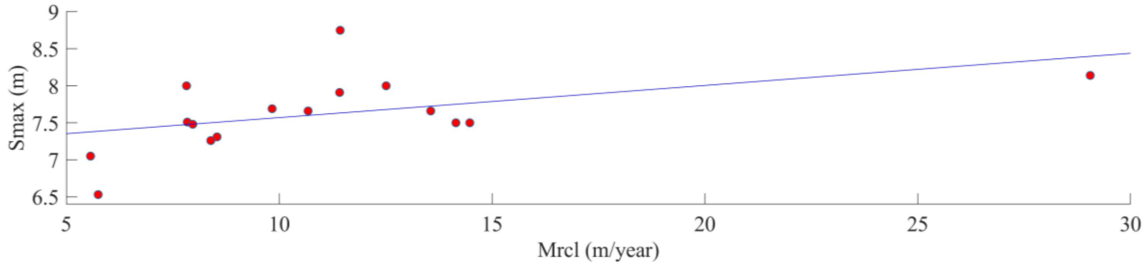

Figure 7. Annual centerline migration rates (M_{rcl}) vs maximum annual stage (S_{max}).

4.2. Bank erosion

The banks of the Ichilo River are constituted of a mixture of soft cohesive material and fine sand with a bank height of around 4 m measured from the water level to the top of the bank at the time of our first field trip (February). The banks in the outer part of the bends have a very steep angle, almost completely vertical. The strength of the banks is affected by the level of saturation showing that moisture content in the bank has an important role (Charlton, 2010) in rivers such as the Ichilo. This is particularly important in Puerto Villarroel where the annual averaged precipitation is between 2000 and 2500 mm (Rejas, 2018) and water levels are highly variable. The decrease and increase of the water levels may affect the behavior of the groundwater table in the banks and therefore, the stability of the banks. This effect was observed by Peters (1998) during the construction of the pilot channels for the human-induced cutoff of 1997 (cutoff #9, Figure 2), where the rainy season started early and the working conditions worsened due to the high groundwater levels.

Another important factor affecting the bank strength is the vegetation found in the Ichilo River, where a dense rainforest can be found especially in the outer banks (Figure 8, right) while in the inner banks grass is abundant, with previous studies suggesting that the predominant species was the West Indian marsh grass (Hymenachne amplexicaulis) (Rejas, 2018). The length of the roots was short (Figure 8, left), affecting the upper part of the banks. This may provide some strength to the banks because the roots of plants have a higher tensile strength meaning they can resist tension (Charlton, 2010).

Figure 8. Bank erosion and vegetation effect in the Ichilo. Left: Grass roots observed in the banks and material collapsed. Right: Dense forest vegetation observed in the outer bank of a bend with a tree collapsed in front of the bank.

4.3 Future planform development

As a result of the analysis we identified two points in the Ichilo river where a future cutoff could develop: cutoff #F1 and #F2 (Figure 2), both points are located near the city of Puerto Villarroel. Orthophotos that were taken during the months of February and May of 2019 (

Figure 9), illustrate the change in the outer banks during four months in cutoff #F1. This section is experiencing erosion from both sides. The change in the distance in the critical section (C) that separates both parts of the river is shown in Figure 10. The short distance in the critical section (less than 100 m) and the type of material suggest that seepage flow may be occurring inside the banks.

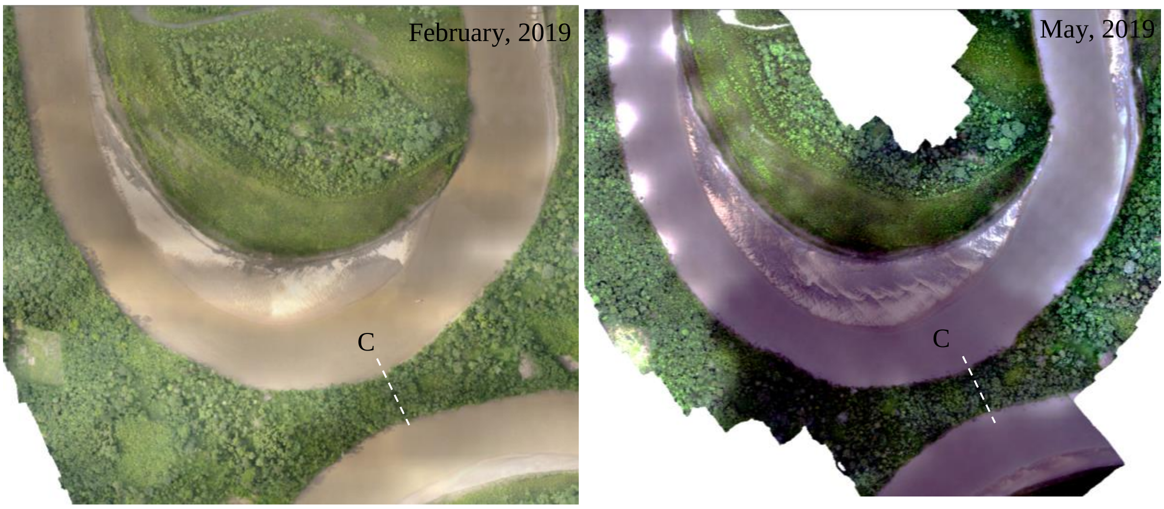

Figure 9. Comparison of the change in the area where cutoff #F1 is expected.

The same situation may be expected in cutoff #F2. When comparing the evolution of the distance in the critical section in both necks #F1 and #F2, we can observe that the distance in #F1 has decreased at a higher rate than the distance in #F2 and therefore, cutoff #F1 is expected to occur first.

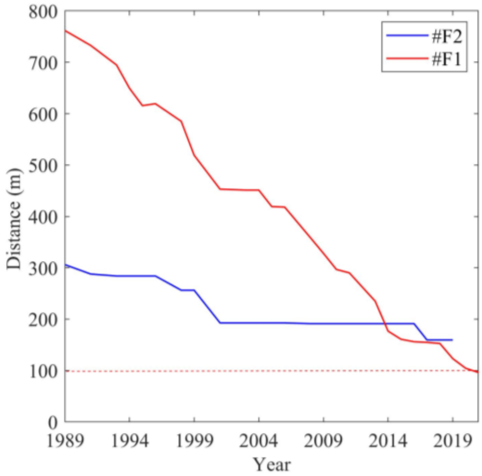

Figure 10. Comparison of the change in the distance in the critical section of cutoff #F1 and #F2

5. CONCLUSIONS

We studied the planimetric evolution of the Ichilo River, a small meandering river in the upper Amazon basin, near the Andes Range. The analysis of the satellite imagery shows that the Ichilo River has high migration rates and that neck cutoff is the dominant mechanism of cutoff occurrence. In addition, the analyzed data showed that the maximum migration rate observed in the Ichilo River was related to ENSO events occurred during 2007-2008. Furthermore, our study suggests that water level variation in the river may affect groundwater table levels in the banks and influence their strength and stability.

Our study concludes that a future cutoff is expected to develop, with two possible scenarios: cutoff #F1 and cutoff #F2. The decreasing rate in the critical section C, indicates that Cutoff #F1 could develop first. The occurrence of this cutoffs will have an impact in the current planform configuration of the river exhibiting the dynamic behavior of Ichilo River.

ACKNOWLEDGMENTS

The authors would like to express their thanks to MEXT for the support to make this work possible, the Nitobe School for providing economical support, the Laboratory of Hydraulics of the Mayor of San Simon University (LHUMSS) and the Servicio Departamental de Cuencas (SDC) in Bolivia for their collaboration.

REFERENCES

Charlton, R. (2010). Channel Form and Behaviour. In *Fundamentals of Fluvial Geomorphology*. https://doi.org/10.4324/9780203371084_chapter_8

Gautier, E., Brunstein, D., Vauchel, P., Jouanneau, J. M., Roulet, M., Garcia, C., Guyot, J. L., & Castro, M. (2010). Channel and floodplain sediment dynamics in a reach of the tropical meandering Rio Beni (Bolivian Amazonia). *Earth Surface Processes and Landforms*, *35*(15), 1838–1853. https://doi.org/10.1002/esp.2065

Gomes, C. H., Sperandio, D. G., & Dessart, R. L. (2018). Remote Sensing analysis of the meanders migration in the Mamorecillo River between 1985 and 2012, Bolivia. *International Journal of Advanced Engineering Research and Science*, *5*(4), 221–228. https://doi.org/10.22161/ijaers.5.4.32

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment. *Remote Sensing of Environment*.

Horton, A. J., Constantine, J. A., Hales, T. C., Goossens, B., Bruford, M. W., & Lazarus, E. D. (2017). Modification of river meandering by tropical deforestation. *Geology*, *45*(6), 511–514. https://doi.org/10.1130/G38740.1

Lombardo, U. (2016). Alluvial plain dynamics in the southern Amazonian foreland basin. *Earth System Dynamics*, *7*(2), 453–467. https://doi.org/10.5194/esd-7-453-2016

Peters, J. J. (1998). Amélioration du transport fluvial en Amazonie bolivienne. *Bulletion of the Belgian Royal Academy of Overseas Sciences*, *44*, 463–482.

Rejas, D. (2018). Trophic structure of a floodplain fish assemblage in the upper Amazon basin, Bolivia. *Revista de Biologia Tropical*, *66*(3), 1258–1271. https://doi.org/10.15517/rbt.v66i3.30693

Schwenk, J., Khandelwal, A., Fratkin, M., Kumar, V., & Foufoula-Georgiou, E. (2017). High spatiotemporal resolution of river planform dynamics from landsat: The rivMAP toolbox and results from the Ucayali river. *Earth and Space Science*, *4*(2), 46–75. https://doi.org/10.1002/2016EA000196

Schwenk, J., Lanzoni, S., & Foufoula-Georgiou, E. (2015). The life of a meander bend: Connecting shape and dynamics via analysis of a numerical model. *Journal of Geophysical Research: Earth Surface*, *120*(4), 690–710. https://doi.org/10.1002/2014JF003252