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Fluvial Dynamics of the Amazon River between Nazareth and Leticia: Potential Loss of Colombia's Sovereignty Over the Amazon River

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Abstract The southern border of Colombia is delimited by the Amazon River, which defines the frontier between Colombia and Peru. Since the 1920s the border limit between these two countries has been defined by the river's thalweg, however the river dynamics has caused changes within its geomorphology making this border line be constantly shifting due to changes in the river's thalweg. This study analyzes the hydrodynamic behavior of the Amazon River and its geomorphological changes within a reach of 3.5 km between the towns of Nazareth (Colombia) and Leticia (Colombia). Through numerical modelling of the river reach, severe sedimentation processes in the left channel were identified, indicating major bed level changes within a 2-year simulation. These bed level changes indicate the appearance of sand bars in the Colombian portion of the river bed. The geomorphological changes shown in the model were validated through the analysis of satellite imagery, which indicates the erosion of the river's right bank, and the sedimentation and contraction of the left bank. These geomorphological changes are causing the loss of river area within Colombian territory, hence meaning that Peru is gaining more river area. If the sedimentation processes continue within the left channel of the Amazon River between Nazareth and Leticia, island formations will increase and it will eventually close, therefore meaning a potential loss of Colombia's sovereignty over the Amazon River.

Keywords Hydrodynamics, Sedimentology, Geomorphology, Erosion, Border Delimitation

1. Introduction

A river is a natural dynamic system that is constantly changing. The hydrodynamic and sedimentological behavior of a river is reflected on its geomorphological changes. However, every river strives to reach its dynamic equilibrium [1], in which both its water flow and sediment transport reach an equilibrium state. Large rivers, such as the Amazon River, are major conveyors of sediment from the continents towards the ocean [2]. This river is generally characterized by its wide floodplains (area where the river is mobile through time) and different channel patterns (single channel to anastomosing reaches) [3].

The dynamism of the Amazon River represents not only a problem from a hydrodynamic and sedimentological point of view, but also from a political and foreign relations perspective, given that currently the river's thalweg represents the border line between the countries of Colombia and Peru. In terms of lateral stability, the Amazon River is clearly different from other anastomosing rivers that show laterally-stable channels [4].

The river's Dynamic represents a constant threat for a clear definition of the border limits between both countries, particularly for Colombia, which takes the risk of losing sovereignty over the river's navigable channel [5]. Potential closure of the right channel of the Amazon River and the merger of islands may generate uncertainty of the border limit between Colombia and Peru, given the river's thalweg could shift completely towards Peruvian territory, leaving Colombia without a clear access to the river. In addition to border line definition, other issues may arise; such as: access to water sources for Colombian towns, prohibition of fishing activities and a decrease in ecotourism in Leticia (Colombia).

This research evaluates the hydro-sedimentological dynamic of the Amazon River between the towns of Nazareth and Leticia in Colombia. The river has shown severe processes of morphological changes given that it is a highly dynamic river, for example bank erosion and island formations within the main channel.

Through mathematical modeling, we seek to evaluate the sedimentological processes in the river, particularly bed level changes, which may represent future isle formations and potential long-term geomorphological changes, which can affect Colombia´s sovereignty over the Amazon River. The effect of dredging the river will be analyzed, as well as its duration over time in order to maintain the channel's navigation conditions within Colombian territory as a possible solution for the border delimitation issue.

2. Background

The border between Colombia and Peru extends through 1.626 kilometers [5] in which the Treaty of Limits and River Navigation between Colombia and Peru, stablishes the starting from the confluence of the Atacuri River and the Amazon River, the border is drawn by the Amazon River's thalweg until reaching the limits between Peru and Brazil [6]. As shown in Fig. 1.

The fact that the border line is defined by a river that is so dynamic as the Amazon River, with a high volume of sediment transport, means that the extension of both countries (Colombia and Peru) is defined by the hydrodynamic and geomorphological behavior of the river [7, 8].

Studies done by the Universidad Nacional of Colombia [9], indicate that the Peruvian bank of the Amazon River has suffered erosion processes, meanwhile the left bank, which belongs to Colombian territory, has accumulated sediments through time. This means that Peru is gaining river, but losing land; while on the other hand in Colombia is happening the contrary. River migration for the Amazon River has been estimated at rates of 213 m per year, near Leticia [10], and 400 m per year in Peruvian territory [11].

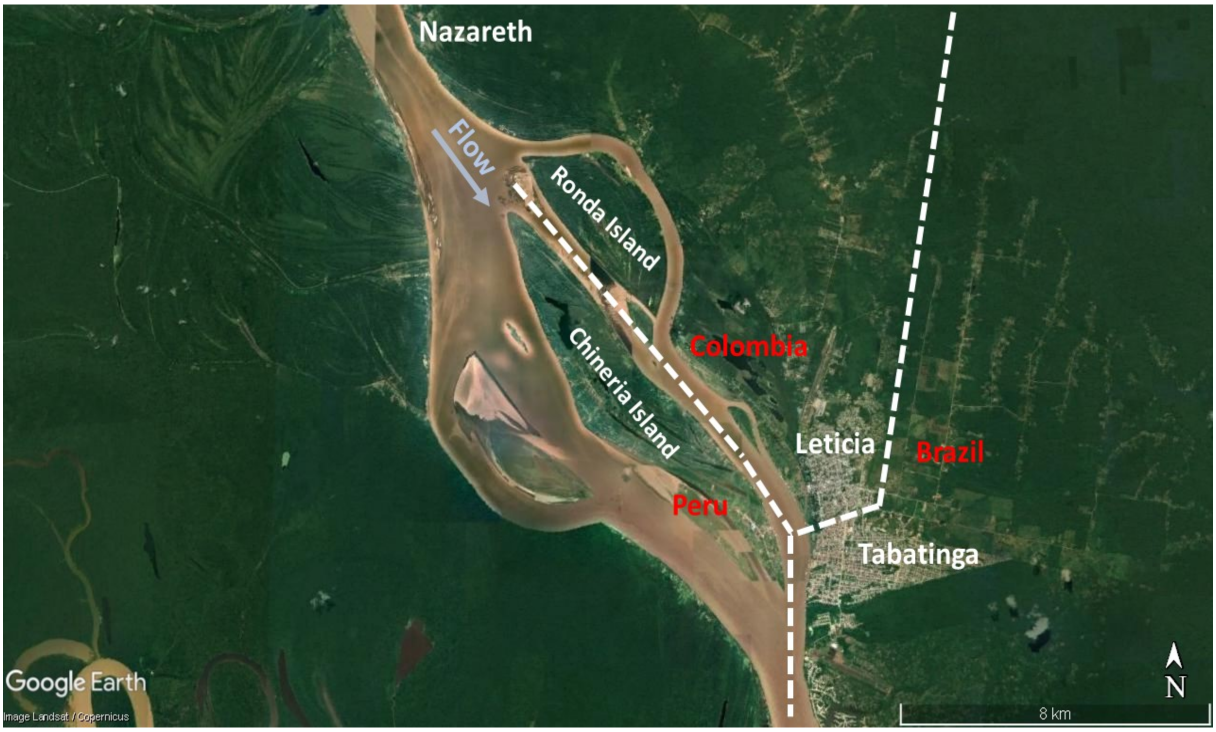

Figure 1. Border limit in the Amazon River between Colombia and Peru

Sediment accumulation on the Colombian riverbank, as well as sandbar formations which have turned into islands [12], represent a severe problem for the river port located in the city of Leticia; which loses its purpose as floating dock during periods of low water levels, hindering its use and posing a threat of permanent closure of the city's port area [13].

Severe sedimentation processes have also generated security issues in terms of the difficulty that the Colombian National Army has to patrol the border; given that the Amazon River has a high fluvial dynamic and constant changes in its thalweg, the main characteristic of the border between Colombia and Peru is that it is constantly shifting [9].

3. Methodology

3.1. Hydro-Sedimentological Modelling

Through numerical 2D-modelling of the study sector of the Amazon River, it was possible to simulate hydrological scenarios that allowed to analyze the hydrodynamic, morphological and sedimentological conditions of the river reach between Nazareth and Leticia; which in turn allowed to understand in a better way the problematic regarding sedimentation processes.

The numerical model used for such engineering analysis is the NAYS2D joined with a graphic interface named I-RIC, developed by the University of Hokkaido (Japan) and the United States Geological Survey (USGS).

The NAYS2D software is a two-dimensional model capable of solving subcritical, supercritical and transitional flows through finite elements coding.

By applying this model results were obtained in terms of current velocity and water surface elevation for each point of the computational grid, which represents the discretization of the flow field. For such purposes, the model solves the continuity and momentum equations in two directions (X and Y).

Sediment transport equations are based in mass conservation principle, assuming that dispersions that may cause by possible waves are negligible [14] [15].

3.2. Digital Elevations Model

The digital elevations model was built from bathymetric information from of July 2019 survey, which spanned through the Amazon River starting from 3.5 km downstream of Leticia, upstream to the town of Nazareth. The digital elevations model was complemented by a bathymetric survey of august 2019 which measured the right channel in Peruvian territory. Fig. 2 shows the complete bathymetric survey used to develop the digital elevation model.

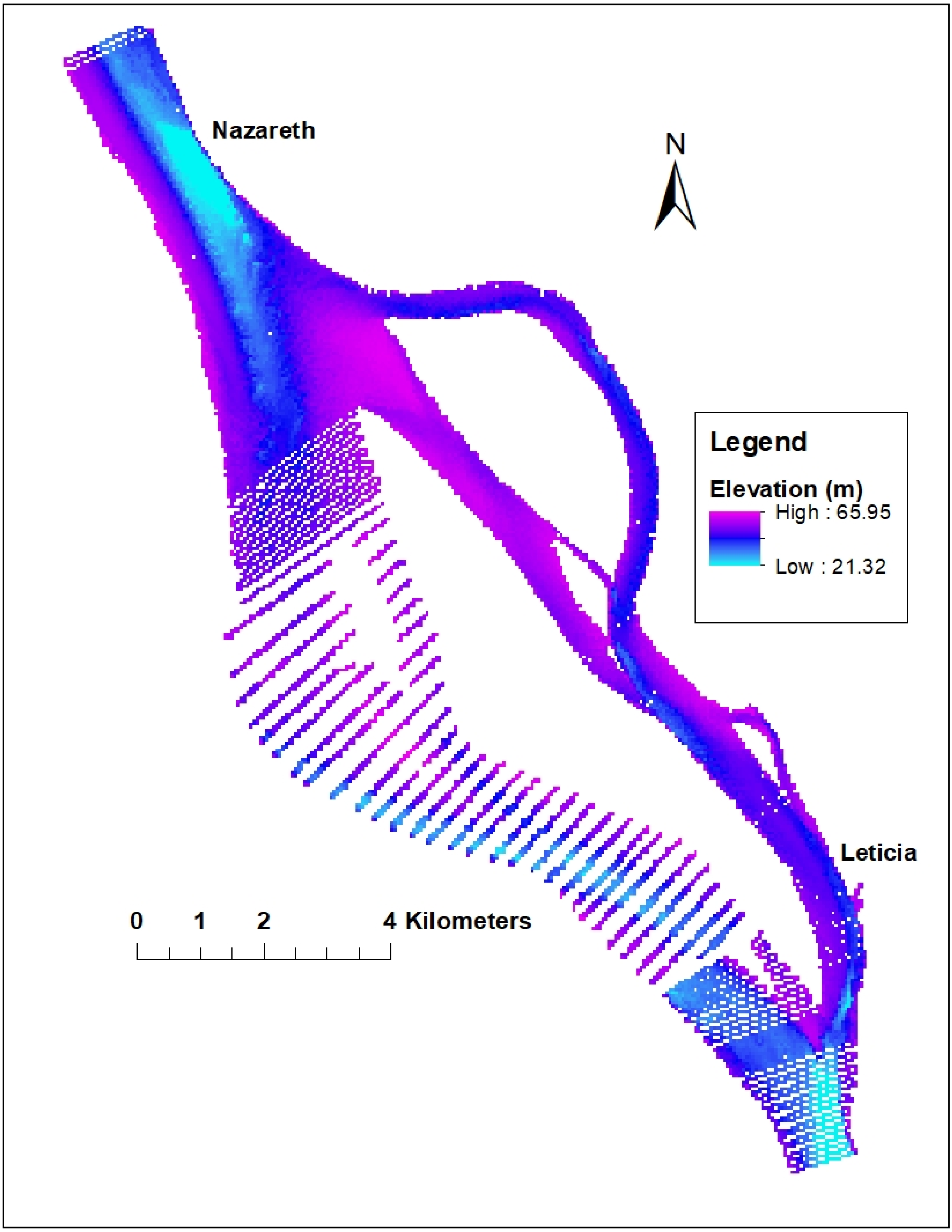

Figure 2. Bathymetric survey of 2019 in the Amazon River from Nazareth (upstream) to Leticia (downstream)

3.3. Computational Grid

Given the length of the river reach in the numerical model, almost 20 km, it was necessary to use a computational grid of a certain cell size that allowed the model to be stable in its calculations, while also optimizing the computational time for each simulation.

A curvaceous computational grid was built with cell size ranging from 60 m x 80 m, up to 200 m x 220 m (Fig. 3).

Figure 3. Computational grid for 2D model of the Amazon River

3.4. Model Calibration

The model was calibrated in both its hydrodynamic and sedimentologic components. In order to achieve proper calibration, official daily records of water surface elevation were used from a limnimetric station located at Leticia's main dock, as well as water elevation and cross-section measurements carried out in field during bathymetric survey campaigns.

For the hydrodynamic calibration, the river's mean flows were simulated from January to July, the outputs from the 2D model in Leticia were then compared with the measured water levels from the daily records of the limnimetric station. Fig. 4 shows the hydrodynamic calibration results for the 2D model of the Amazon River, comparing the model's output with real water elevation measurements. Water level results from the model adjusted very well to the observed water levels with a coefficient of determination of R^2=0.9911. Precipitation is responsible for the amplitude in the annual water level fluctuation [3].

For sedimentological calibration bed level changes were compared between an initial bathymetric survey from July 23rd and a final bathymetric of October 22nd. The purpose was to reproduce the same bed level changes with the numerical model, for which three cross-sections were analyzed within the river reach; cross-section number 1 is located in Leticia, cross-section number 2 is 4.3 km upstream of Leticia and cross-section number 3 is located in Nazareth.

For sedimentological calibration, a bed size material with D_{50} = 0.3 mm was used [16]. Fig. 5, Fig. 6 and Fig. 7 show the results for the sedimentological calibration of the 2D model of the Amazon River. The coefficients of determination (R^2) for sedimentological calibration were 0.923, 0.867 and 0.883 for cross-sections 1, 2 and 3, respectively.

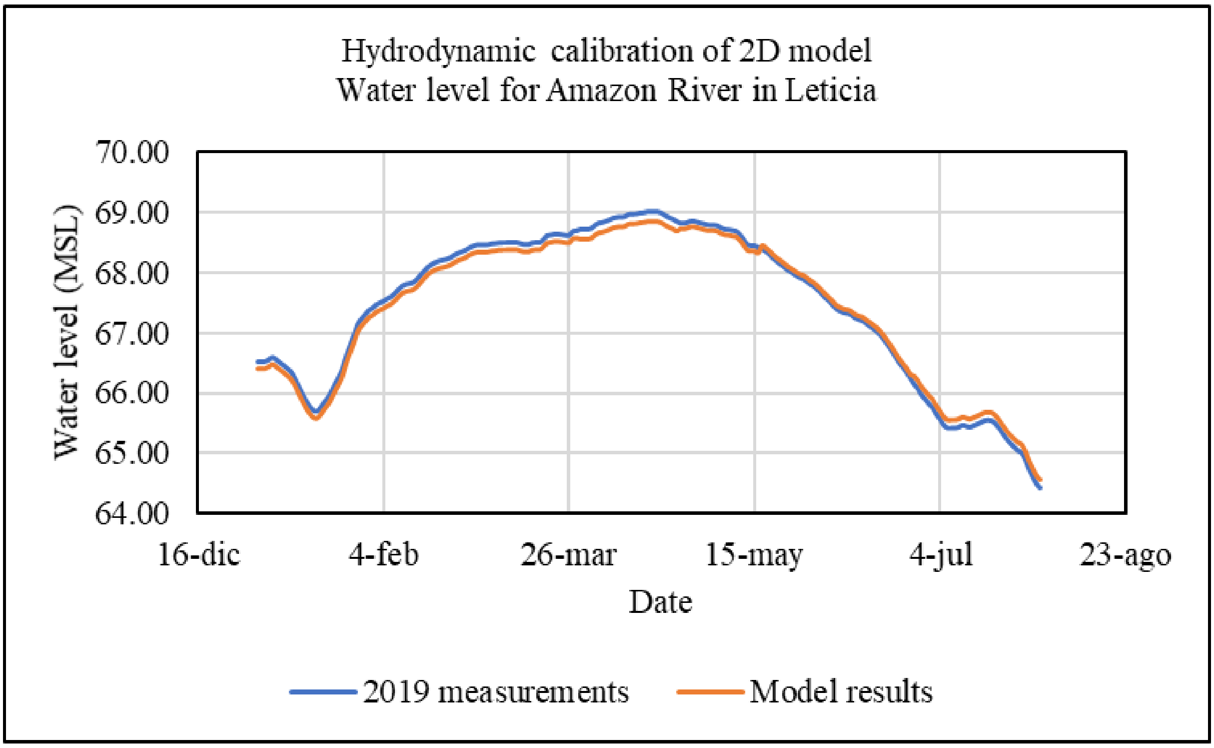

Figure 4. Results of the hydrodynamic calibration of 2D model

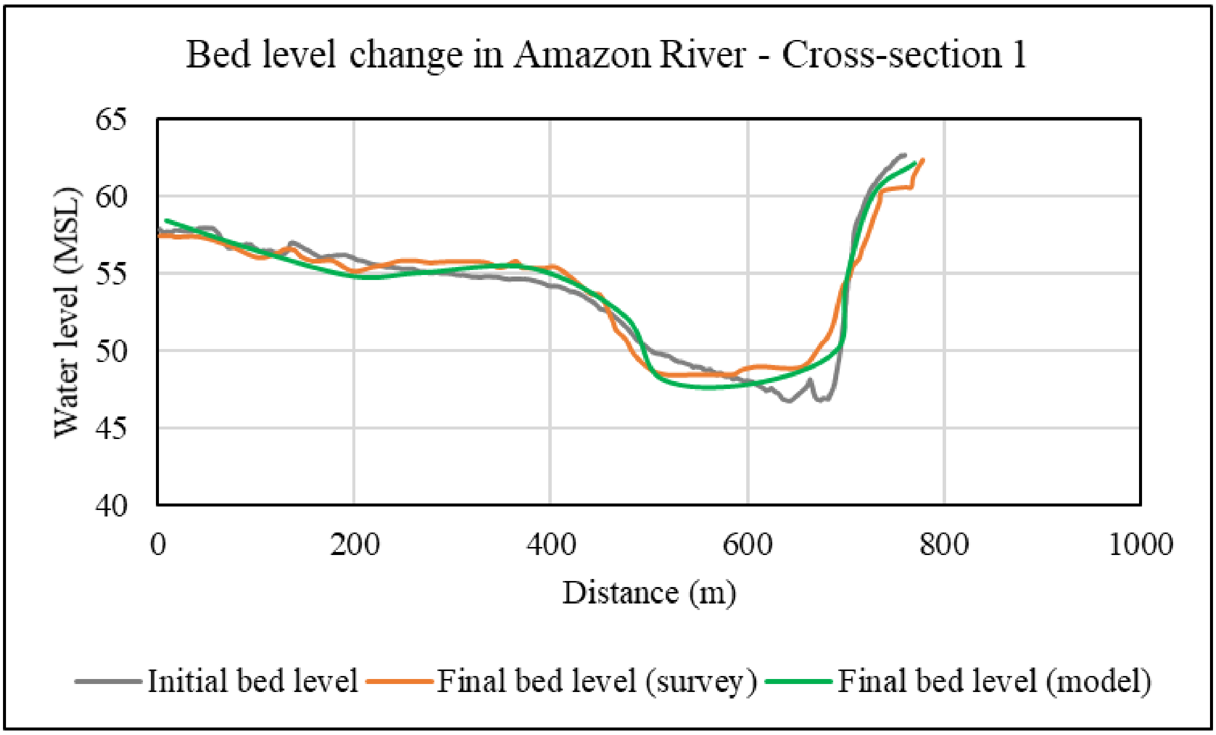

Figure 5. Sedimentological calibration for cross-section 1

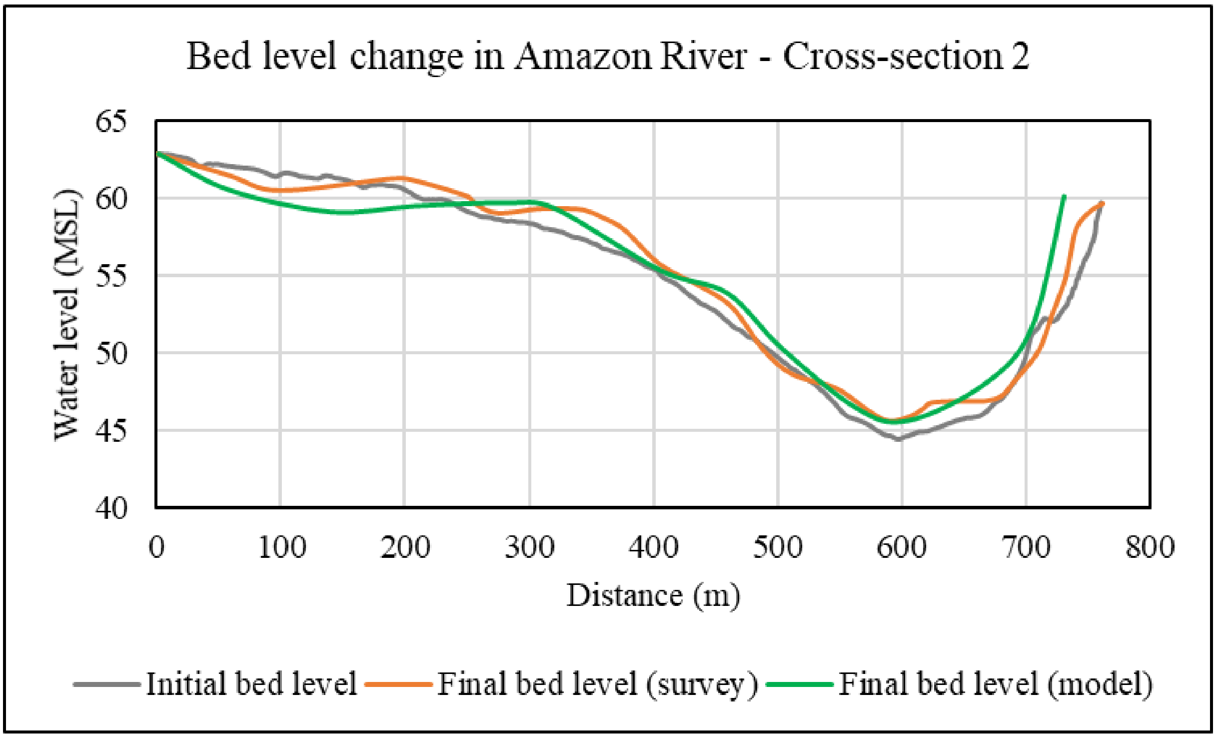

Figure 6. Sedimentological calibration for cross-section 2

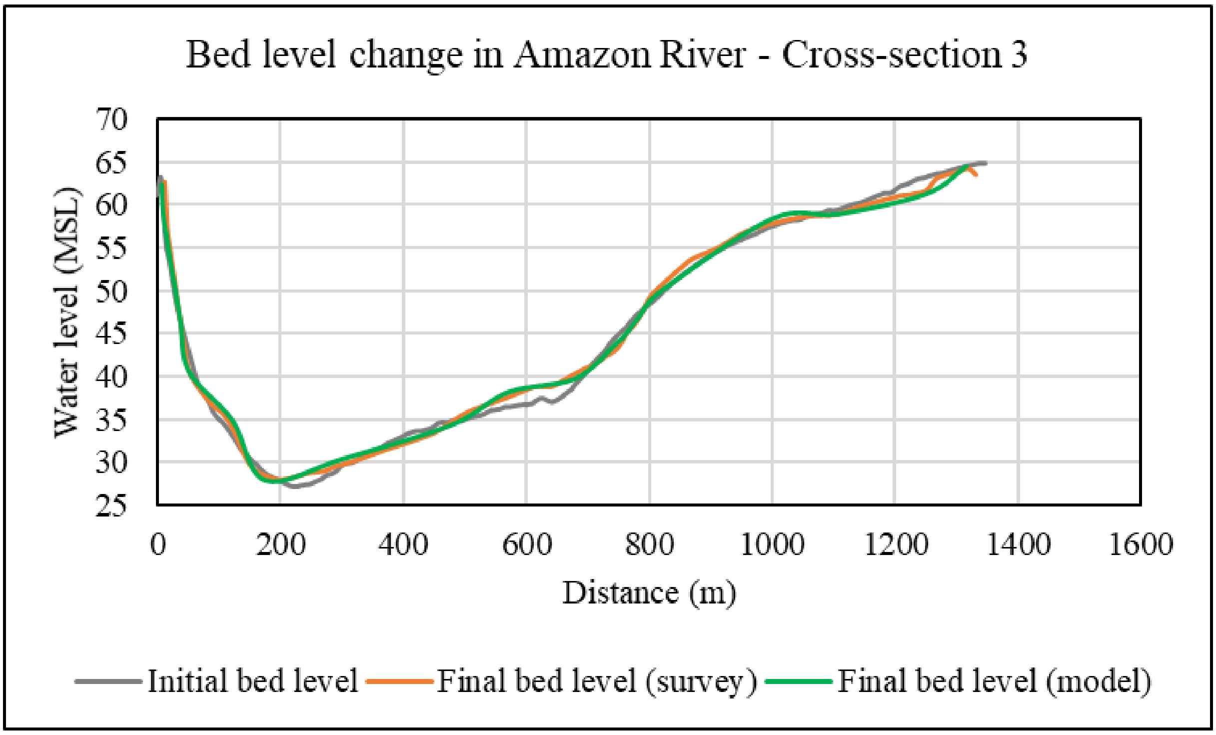

Figure 7. Sedimentological calibration for cross-section 3

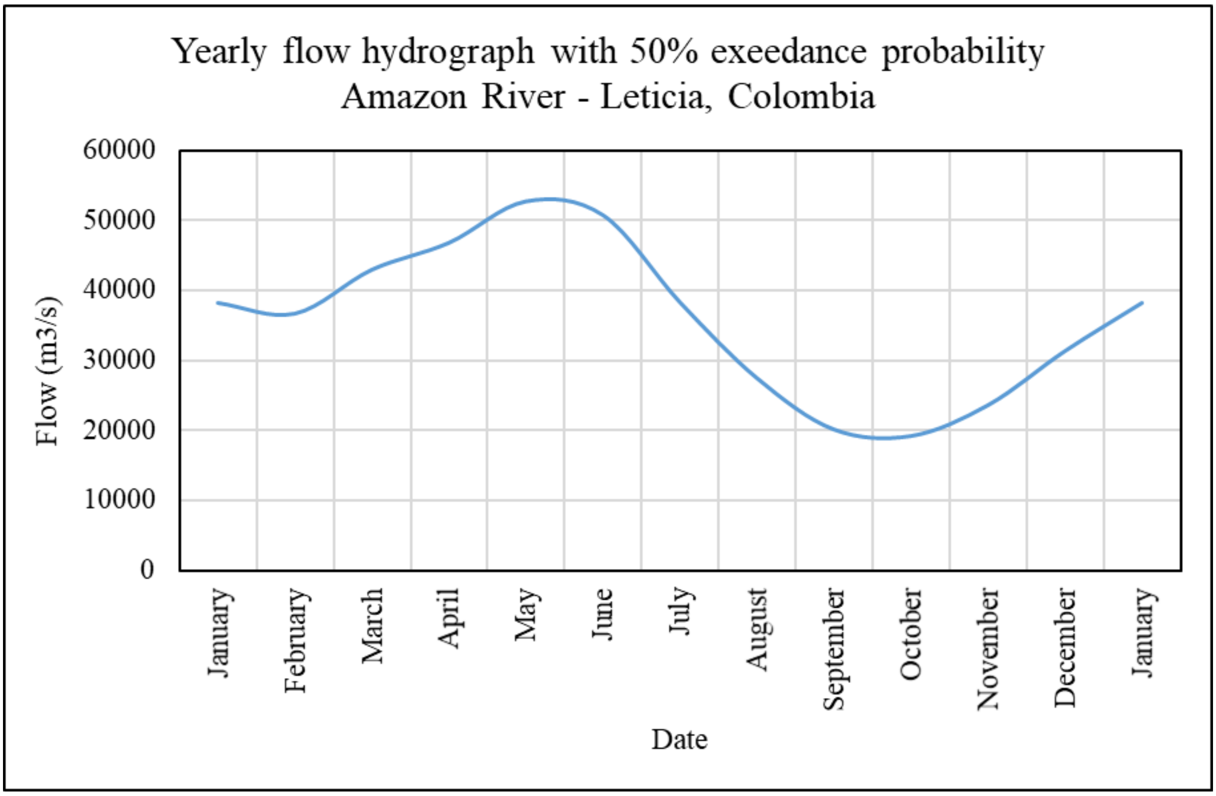

Figure 8. Flow hydrograph with 50% exceedance probability used for 2D simulation.

3.5. Hydrological Scenario

The hydrological scenario simulated for the Amazon River was the mean flows hydrograph (50% exceedance probability), in order to evaluate the river under mean hydrological conditions. A full year of river flow time series was simulated which in turn increased the total simulation time (27 hours). Fig. 8 shows the 50% exceedance probability hydrograph simulated with de two-dimensional model. 50% exceedance probability hydrograph represents medium flow conditions of the river, showing water flow values associated with a return period of 2 years.

4. Results

The 2D model simulated two consecutive years of the 50% exceedance probability hydrograph, obtaining outputs for the hydrodynamic (water surface elevation and current velocity) and sedimentological behavior (bed level changes) of the Amazon River between Nazareth and Leticia. The outputs gathered with the 2D model were used to validate geomorphological changes observed in the river through satellite imagery, which indicate a potential closure of the river's left channel in Colombian territory. The results are shown and discussed below.

4.1. Fluvial Dynamics

Outputs regarding bed level changes were interesting to analyze during the two years simulation. Severe sedimentation processes were shown in the river's left channel (Colombian border), particularly at the entrance and exit of Ronda Island, north of Leticia. Fig. 9 and Fig. 10 show the results for bed level changes in the river after 3 months and 24 months of simulation time, respectively. Sedimentation processes over the river bed are shown in red color, especially high sedimentation areas (over 3.0 m of sedimentation).

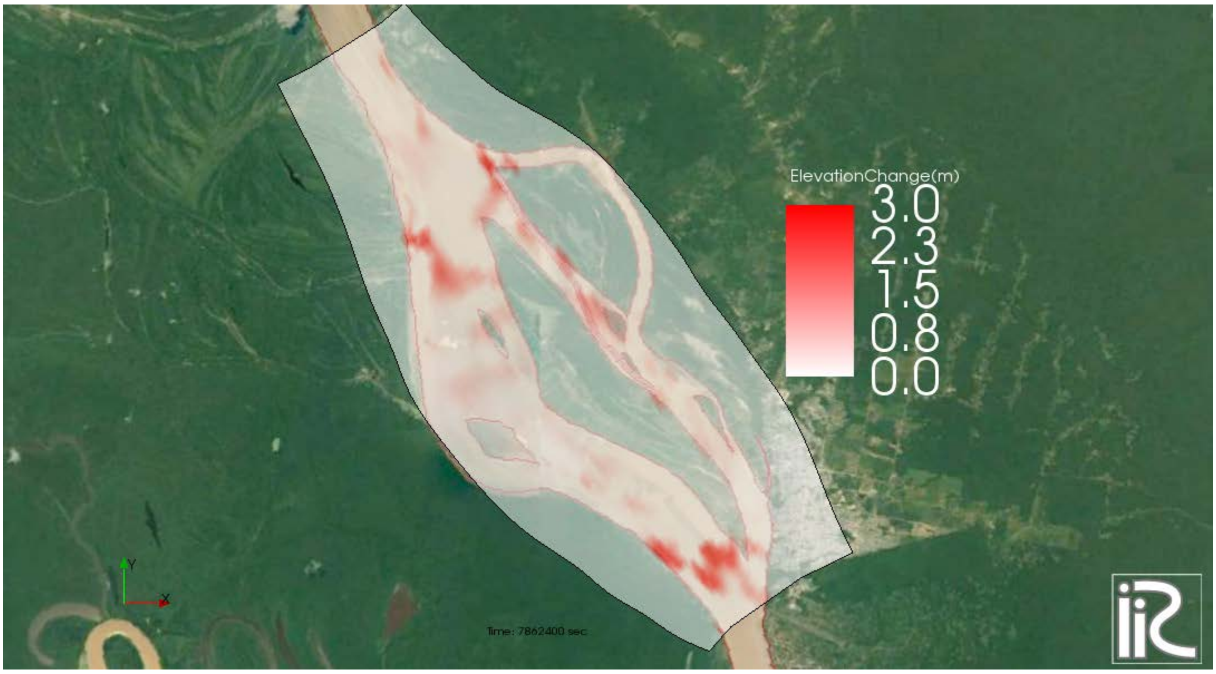

Figure 9. Bed level change results after 3 months of simulation.

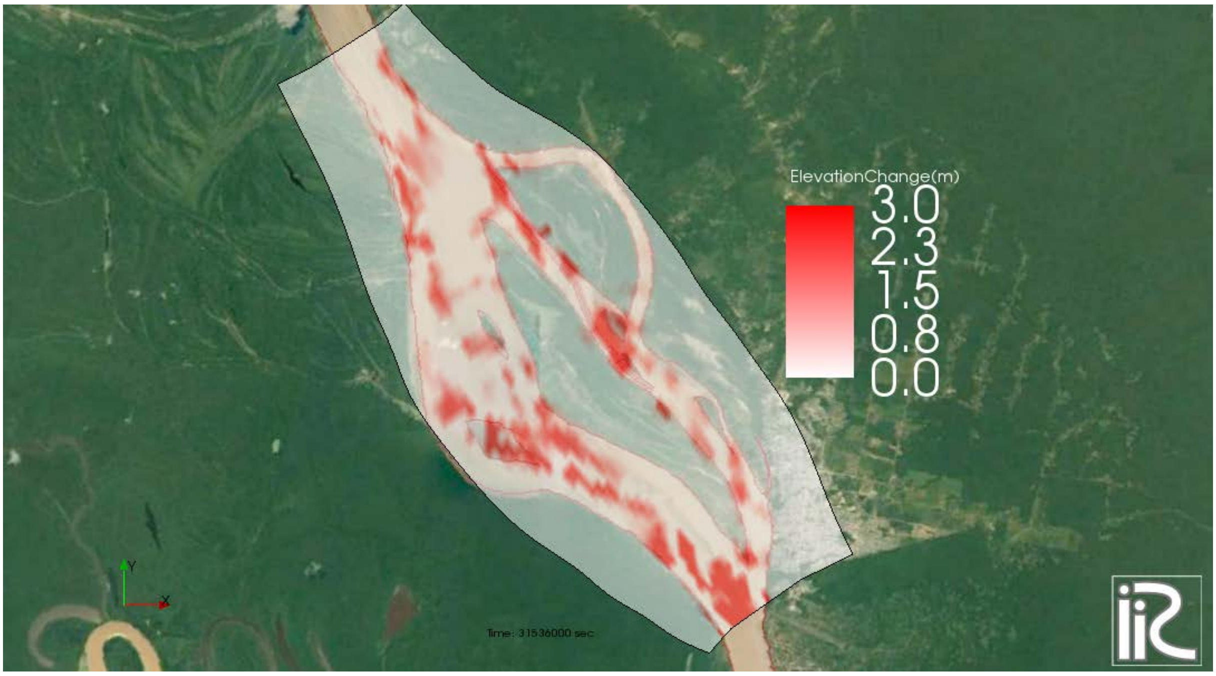

Figure 10. Bed level change results after 24 months of simulation.

Fig. 9 shows hints of sedimentation processes over the left channel (Colombia). Fig. 10 shows very clear processes of extreme sedimentation at the entrance and exit of Ronda Island, indicating a potential closure of this channel. The sedimentation area at the exit of Ronda Island concurs with the current formation of a sandbar in that same spot on the riverbed. Therefore, if this sedimentation process continues, the sandbar will keep increasing through time, turning into an island, potentially leading to a complete restriction of water flow over the left channel of the Amazon River. Islands may be formed by avulsion or developed from within-channel sediment deposition [17].

Sediment accumulation over the left channel of the Amazon River, in Colombian territory, is also directly linked to the river's hydrodynamic behavior. In the case of Ronda Island, the shear stress generated by the water stream at the entrance and exit range from 0.5 Pa to 1.8 Pa, which are low magnitudes compared to the shear stress shown in the main channel, with values reaching over 20 Pa. Low shear stress promotes bed sedimentation downstream, hence the sediment accumulation observed on the left channel.

The hydrodynamic and sedimentologic conditions previously explained, generates geomorphological changes on the riverbed. These geomorphological changes, suggested by the model can be validated by an analysis of satellite imagery. Fig. 11, Fig. 12, Fig.13 and Fig. 14 show historical Landsat imagery for the Amazon River in the study reach for 1984, 2008, 2014 and 2021, respectively.

Between the years 1984 and 2008 the fluvial dynamics of the Amazon River is marked by great geomorphological changes; particularly the erosion and movement of the river's right bank (Peru), expanding the right channel and therefore widening the main channel towards Peruvian territory. Sedimentation processes can also be observed over the left bank near Leticia, contracting the left channel and therefore reducing the width of the channel in Colombian territory [12].

In 2014 a small island began to form immediately downstream of Ronda Island. This small island is formed in the same sector of high sedimentation processes shown by the outputs of the numeric model. Finally, for the year 2021, this same island had grown in size, reaching up to 530 m wide. The formation of the new island goes hand in hand with the appearance of various sandbars as a product of severe sedimentation in the left channel (Colombia). An island is formed when recent deposition becomes colonized by vegetation [3].

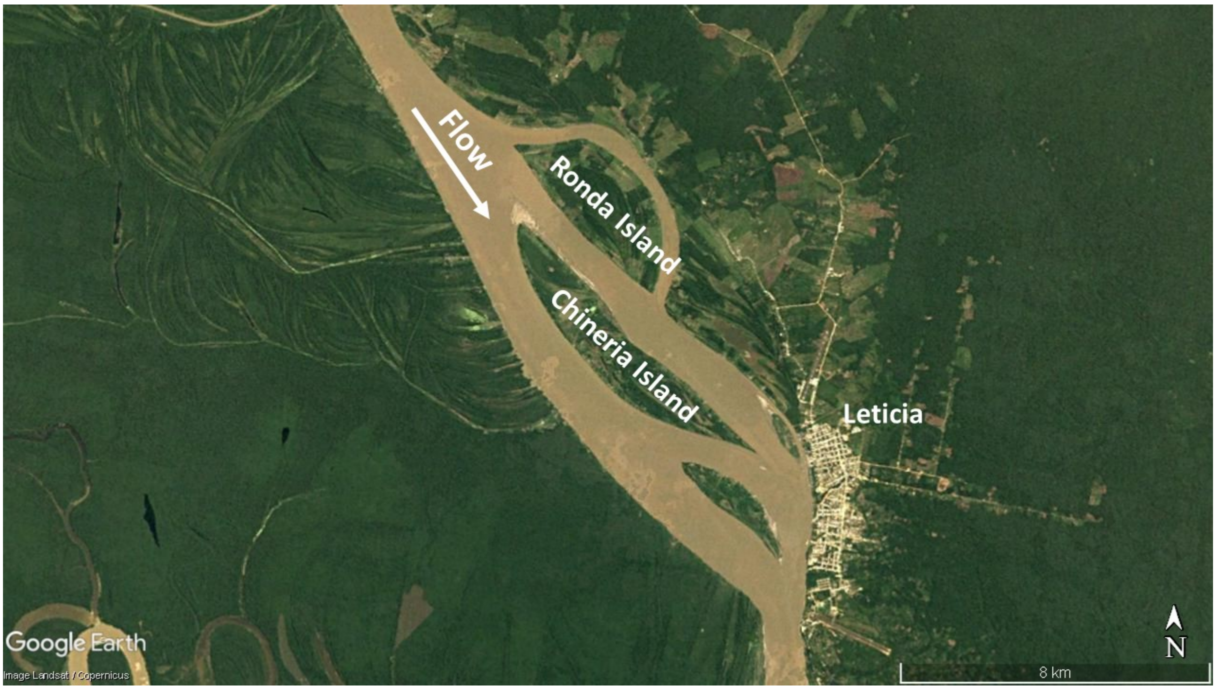

Figure 11. Landsat image of the Amazon River in December 1984

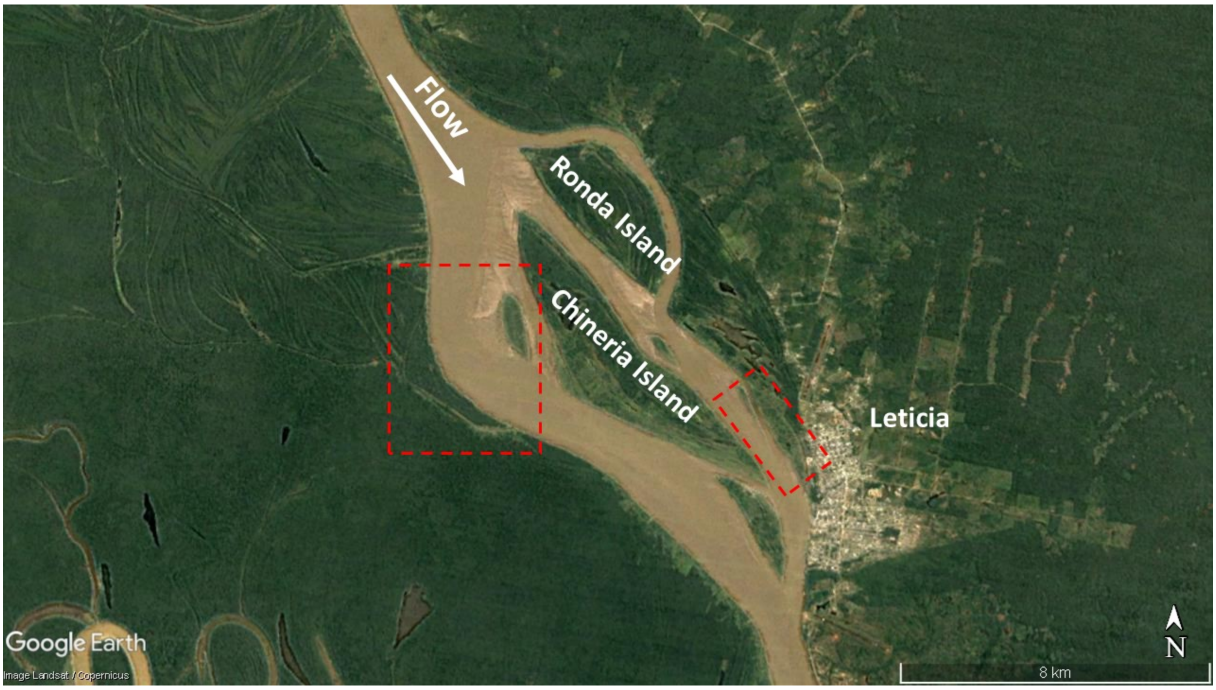

Figure 12. Landsat image of the Amazon River in December 2008

Figure 13. Landsat image of the Amazon River in December 2014

Figure 14. Landsat image of the Amazon River in December 2021

A study done by Rozo et al. [3] in which satellite imagery of the Colombian Amazon River was analyzed pixel by pixel, showed that changes plain view of channels, islands and floodplains reflect a clear accretion and emergence of new islands. The general tendency of the Amazon River is towards deposition, despite erosion being predominant between 1994 and 2001. Rivers tend towards a state of equilibrium in which erosion processes in one part of the river are balanced by deposition processes on another part [18] [19].

4.2. Potential Change of Sovereignty

The strong sedimentation processes over the river's left channel have led to the formation of islands on the riverbed and the constant advance of the river's left bank. Thus, making smaller the Colombian portion of the river channel each year. The river is not only moving towards the right bank, increasing the surface area of the river in Peruvian territory, but also generating a potential and definite closure of the entire left channel. Although the Colombian reach of the Amazon River can be classified as a meandering multichannel river [20] [21], this may change in further years if geomorphological changes continue.

If sedimentation processes continue the left channel of the Amazon River, it will be completely close with no water flow, meaning that Colombia would lose sovereignty over the river. This also has serious implications over the definition of the border line between Colombia and Peru, which is currently defined by the river's thalweg on the left channel. The implications of losing sovereignty over the Amazon River, would have major economic consequences for the people of Leticia; activities such as, ecotourism and the transportation of goods through the river will be seriously diminished by the lack of a navigable channel. Similar consequences have happened in river borders, such as the Ara River which serves as a frontier between Iran, Azerbaijan and Armenia. In this case the Ara River presented a 30 m displacement from the Iranian bank causing a water shortage emergency [22].

A possible solution for this problem is to carry out periodic dredging works over the left channel of the Amazon River, counteracting the formation of future sandbars that can lead towards a permanent closure of this water stream. Dredging volumes were calculated from bathymetric measurements for a navigable channel of 8.0 km long on the left channel. Table 1 shows the calculated dredging volumes for different channel widths at different dredging levels.

Table 1. Dredging Volumes (cubic meters)

Dredging level (MSL)	Width: 100 m	Width: 120 m	Width: 150 m
56.0	2,800,000	3,300,000	4,100,000
55.0	3,800,000	4,400,000	5,400,000
54.0	4,800,000	5,600,000	6,800,000
53.0	5,800,000	6,800,000	8,200,000
52.0	6,900,000	8,000,000	9,600,000

The dredging of the Amazon River on its left channel can be done periodically in order to guarantee the removal of sandbars and sediment pockets, allowing a permanent flow of water over the left channel [23].

If no solution is implemented on the left channel, the river will continue its sedimentation tendency until it reaches a point in which the entire water flow will pass only through the right channel (Peru); to the point that eventually the Chineria Island will merge with the river's left bank, in which case Colombia would have loss complete sovereignty over the Amazon River. This scenario will lead to political issues in terms of defining a clear frontier between Colombia and Peru. On one hand the Treaty is clear in stating that Chineria Island belongs to Peru, in which case Colombia would lose completely its access to the Amazon River; on the other hand, the Treaty expresses that the border line is defined by the river's thalweg, which would be non-existing given that the left channel might be completely close.

The uncertainty regarding potential loss of sovereignty over the Amazon River raises many concerns for Colombia; issues like water availability for the population of Leticia in case of a total closure of the left channel, economic decline due to ecotourism that used to revolve around the Amazon River, fishing activities and transport of goods, are some of the more troublesome topics regarding the Amazon River for Colombian government. Anticipating such scenarios is key in order to take the appropriate measures.

5. Conclusions

Currently, the frontier between Colombia and Peru is defined by the Amazon River, thus, meaning that the border line is constantly moving and shifting due to geomorphological changes of the river throughout the years.

Through numerical modeling outputs and by analyzing historic satellite imagery, it is confirmed that the Amazon River is moving towards Peruvian territory. Erosion processed on the river's right bank and sedimentation of the left bank are generating a loss of river coverage within Colombian territory.

Sedimentation processes generated by low shear stress over the left channel have favored the formation of islands and the contraction of the channel's width. If such sedimentation was to continue, then the permanent closure of the left channel is imminent, hence leading to a total loss of sovereignty of Colombia over the Amazon River.

The maintenance dredging works over the river's left channel are a temporary solution in a short term, but don't address the need to channel the water stream towards the left canal. Further studies must be conducted, evaluating solutions oriented towards river training, which may allow the river to regain its condition of morphological stability in the left channel, and therefore allowing the clearer border line to be defined between Colombia and Peru.

Possible solutions for this issue must involve not only engineering works but also political will and cooperation in order to guarantee a clear border line between both countries. Open and transparent discussions about the river's dynamic should be carried out between Colombia and Peru, because the link between nature, territory and law involves both countries [22] [24]. Therefore, solutions may be conceived as a collaborative work that impacts two countries and not only as individual attempts to modify the river's dynamic, keeping in mind that any alteration might end up affecting both Colombia and Peru.

In addition to dredging works, the river must be constantly monitored in both reaches (Colombian and Peruvian) through bathymetric surveys, discharge and sediment transport measurements. Other solutions might consider building river dams [22] through collaborative work between Colombia and Peru, in order to channel the river towards the Colombian reach.

The results from this study can be useful for geomorphological analysis in riverine borders with similar hydrological and political characteristics; in order to have a better understanding of border dynamics and help reach governmental management policies regarding water resources to avoid future issues.

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