

Geomorphological Changes in the North Channel of the Amazon River (2011–2024): Impacts on Navigation in Macapá Bay

Mudanças Geomorfológicas no Canal Norte no Rio Amazonas (2011–2024): Impactos Para a Navegação na Baía De Macapá

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Abstract

The North Channel of the Amazon River is a vital navigational gateway to the Amazon Basin. This paper analyzes the geomorphological evolution of the channel between 2011 and 2024, and assesses the observed morphodynamic processes, while also quantifying the differential uncertainty of the different sources of data. This analysis was based on a rigorous standardization process, which reprojected the multibeam survey data (2011) and digitized the nautical chart data (2024) to the SIRGAS 2000 metric system/UTM Zone 22S. This approach used ordinary kriging interpolation with individually fitted Gaussian models. The cross-validation of the results provided a measure of the disparity in the precision between the sources, revealing a low Root Mean Square Error (RMSE) of only 1.16 m for the 2011 model and a moderate, well-characterized error of 5.25 m for the 2024 model. The geomorphological analysis indicated a marked trend of silting, with mean depth decreasing from 26 m to 22 m, and the migration of the channel toward the east-northeast. These findings indicate that the safe management channel depends on an integrated approach that incorporates an accurate measure of this uncertainty. This analysis reinforces the need for continuous bathymetric monitoring, and supports the need to adopt adaptive navigational strategies, such as dynamic draft, to ensure operational safety in this complex fluvial system.

Keywords:

Bathymetry, Fluvial geomorphology, Sedimentation, Hydrodynamics.

Resumo

O Canal Norte do rio Amazonas é uma porta logística vital na Bacia Hidrográfica do rio Amazonas. Este artigo analisa a evolução geomorfológica do canal, no período de 2011 a 2024, avaliando os processos morfodinâmicos e a quantificação da incerteza diferencial das fontes de dados. A

metodologia empregou um rigoroso processo de padronização, reprojetoando os dados de levantamento multifeixe (2011) e de digitalização de carta náutica (2024) para o sistema métrico SIRGAS 2000 / UTM Zone 22S. A interpolação por krigagem ordinária, com modelos Gaussianos ajustados individualmente, foi utilizada. Os resultados da validação cruzada quantificaram a disparidade de precisão entre as fontes, revelando um baixo erro (RMSE) de 1,16 m para o modelo de 2011 e um erro moderado e conhecido de 5,25 m para o modelo de 2024. A análise geomorfológica revelou uma tendência de assoreamento, com redução da profundidade média de 26 m para 22 m, e uma migração do canal para leste-nordeste. Conclui-se que a gestão segura do canal depende de uma abordagem que incorpore essa incerteza quantificada. A análise reforça a necessidade de monitoramento batimétrico contínuo e valida a adoção de estratégias de navegação adaptativas, como o calado dinâmico, para garantir a segurança operacional neste complexo sistema fluvial.

Palavras-chave:

Batimetria, Geomorfologia fluvial, Sedimentação, Hidrodinâmica.

I. INTRODUCTION

The Amazon River forms the World's largest tropical basin, and encompasses a complex network of rivers, channels, lakes, and islands that undergo continuous change driven by the sedimentation, transport, and deposition of Suspended Particulate Matter (SPM). On average, the Amazon River discharges $175,000 \text{ m}^3 \text{ s}^{-1}$ of freshwater into the Atlantic Ocean, with the discharge peaking at $250,000 \text{ m}^3 \text{ s}^{-1}$ in the rainy season month of May, dipping to $110,000 \text{ m}^3 \text{ s}^{-1}$ in the dry season month of November (Sampaio; El Robrini, 2024), with a solid load of 1,200 Mt/year (Milliman; Farnsworth, 2011). The North Channel, like the rest of the Amazon region, is dominated by macrotides with a maximum amplitude of 4 m (spring tide) and 2.7 m (neap), and minimum amplitudes of 0.3 m and 0.5 m during the spring and neap tides, respectively (Brazilian Navy Hydrography Center, 2025). Waves generated by the local northeasterly trade winds can also reach a mean height of 1–2 m (Kosuth; Callède; Laraque, 2000).

The monitoring of the geomorphology of fluvial channels is essential to guarantee the safety of shipping and navigation. The North Channel of the Amazon is located in the estuarine reach of the river (Galindo et al., 2021), on the southern margin of the Brazilian state of Amapá, which includes a number of ports, including the Santana shipping complex. The channel provides access to these ports, and is considered to be one of the principal navigable waterways of Northern Brazil, where it plays a pivotal role in the region's economy and social development.

Annually, some 2.5 million tons of grain — 80% of which is soybean — pass through the region (National Waterway Transportation Agency, 2024). The Port of Santana, in the Brazilian state of Amapá, is one of the

principal hubs of this commerce. The shipping that flow. The fleet transiting the area is diverse, with a notable presence of foreign flagged vessels, underscoring the port complex's relevance to international trade. Given the channel's strategic importance, the port region of Amapá undergoes periodic dredging—the most recent in 2024—due to its strategic position in the Amazon River estuary, which is subject to sediment input from the Amazon River (Companhia das Docas de Santana, 2024).

This channel is influenced by hydrological processes and is situated in a region of high water and sediment discharge. The intense semidiurnal tidal regime, combined with seasonal variations in hydrology (dry from September to May and rainy from June to August) and high precipitation rates averaging > 3,000 mm/year, exerts significant control over channel migration (Less et al., 2021). The high rainfall typical of the Amazon region also contributes to increased river discharge, influencing the channel's geomorphology (Fassoni-Andrade et al., 2023).

Fluvial channels exhibit geomorphological features that reflect the complex processes of erosion, sediment transport, and deposition over time (Bastos et al., 2019). These features include meanders—sinuous bends that develop as flow navigates geological obstacles due to spatial variations in flow velocity. In addition, sand bars frequently form on channel beds, resulting in zones of sediment accumulation that can alter local hydrodynamics (Fricke et al., 2019). As reported by Santos et al. (2022), access channels can be classified into three types—U, R, and C. U-type channels provide the most favorable vessel access, R-type channels are typically adjacent to one bank and have undergone dredging, whereas C-type channels are the most constrained and have a comparatively higher thalweg.

II. MATERIALS AND METHODS

The study area encompasses the North Channel of the Amazon River (0°4'12.99"N, 50°52'54.33"W), which is located in the estuarine portion of the river, and constitutes a dynamic environment influenced by a range of physical processes, such as winds, river discharge, and tidal currents, and the sedimentation resulting from the interaction of these processes (Figure 1). Seasonal shifts in rainfall rates and river discharge play a crucial role in the long-term modification of the geomorphological characteristics of the study region.

Northeasterly trade winds, with mean wave heights ranging between 1 m and 2 m, play a fundamental role in the region's hydrodynamics, affecting both the circulation of the water and the distribution of the sediments within the channel (Siqueira et al., 2020). These wind-driven currents influence the formation of sand- and mudbanks by generating waves that alter the velocity and direction of marine currents, which results

in the continuous movement and rearrangement of the sediments. The interaction between these winds and the tidal currents can intensify both erosive and depositional processes, promoting the formation of sedimentary deposits within the channel.

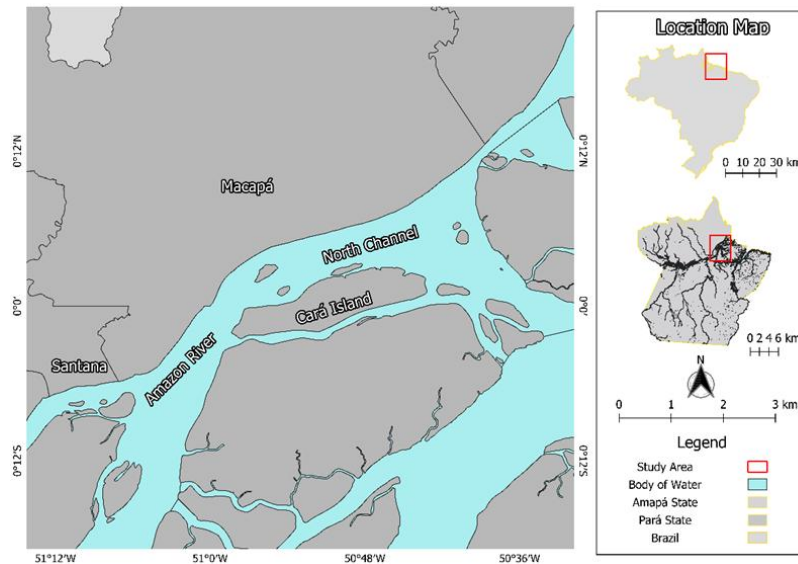


Figure 1 – Location of the study area, highlighting the North Channel of the Amazon River, Cará Island, and the Amazon River. Source: the authors.

The local tides influence the dynamics of the North Channel, with a semidiurnal regime reaching amplitudes of up to 4 m (spring tide) and 2.7 m (neap tide), with minimum values of 0.3 m and 0.5 m, respectively (Brazilian Navy Hydrography Center, 2025). This oscillation controls the exchange of fresh- and saltwater, and promotes the transport of fluvial and marine sediments within the channel. The tidal currents associated with this seasonal variation alter the distribution of the sediments, which has a direct effect on the formation of the sand- and mudbanks, the features that contribute most to the shifts in the geomorphology of the channel (Hoitink; Jay, 2016; Dias et al., 2023).

The enormous discharge of the Amazon River, with a mean of 175,000 m³/s, ranging from 110,000 m³/s in the dry season to 250,000 m³/s in the rainy season, results in intense sediment transport to the North Channel (Anthony et al., 2010; Constantine et al., 2014). The volume of this discharge, combined with seasonal variation in rainfall and the increasing flow observed during the rainy period, contributes to the deposition of sediments within the channel, which forms the sand- and mudbanks (Brêda et al., 2020).

Sedimentation is more intense during the rainy season, when the volume of the river increases considerably, contributing to the deposition of fine- to medium-sand grains in different portions of the channel, whereas other areas may accumulate finer sediments (i.e., silt and clay). This variation in the deposition of sediments causes shifts in the depth and morphology of the channel, which potentially affects navigation and

requires periodic dredging to ensure the safe passage of vessels (Fagundes et al., 2021). During the rainy season (December through May), the mean solid load of the Amazon River (1,200 Mt/year) increases, altering channel dynamics and leading to greater sediment transport and deposition. This increase in river discharge is accompanied by strong tidal currents, which change the geodynamics of the estuarine environment as a whole (Getirana; Paiva, 2013). During the dry season (July - September), by contrast, the reduction in river discharge leads to a decrease in sediment transport, which yields greater stability through the formation of sedimentary banks. The seasonal cycle is key to the understanding the geomorphological changes that occur in the region and how vessels must adapt to the navigability of the channel (Zanin et al., 2024).

The geomorphological irregularities of the North Channel arise from the interaction of oceanographic and hydrological processes — such as sediment input, tides, and fluvial discharge — which reconfigure the system via sediment transport, resulting in zones of deposition and erosion. The North Channel are morphologically dynamic, with meanders, sandbanks of up to 15 m in height, and fluvial islands (e.g., Cará Island, Figure 1), as well as variation in depth that often shifts seasonally. The depositional and erosive processes of this system are amplified by the combination of high discharge volumes and the semidiurnal tides, which result in frequent changes in the bottom substrate of the estuary (Rudorff; Melack; Bates, 2014).

Previous studies of the geomorphology of the Amazon River estuary indicate that channels such as the North Channel have a complex configuration, which is shaped by the interaction between river discharge and tidal currents (Fassoni-Andrade et al., 2020). These continuous changes in channel geomorphology are reflected directly in the intense hydrological activity and sedimentary processes that characterize the region. Navigation in the North Channel is affected by geomorphological shifts and hydrodynamic processes within the channel. The shipping of grain and other commodities, such as soybean, is one of the region's main economic activities, with the Port of Santana being one of the region's principal export hubs (Silva; Tobias, 2023). However, local shipping faces a major challenge from shifts in the depth of the local navigation channels, which requires frequent dredging (Schaeffer et al., 2023).

In this scenario, periodic dredging is necessary to ensure that the channel provides an adequate draft for local shipping, especially during periods of intense sedimentation, reinforcing the need for continuous monitoring to guarantee the safety of navigation in these waters (Lewis; Rhoads, 2015). The seasonal variability in the sedimentary deposits formed within the channel demands that shipping and docking operations are adjusted continuously to the prevailing conditions within the estuary, with direct implications for the mobility of commercial navigation in the region.

Methods

The analysis of the geomorphological evolution of the North Channel was based on the comparison of the bathymetric data from two distinct periods: 2011 and 2024. The 2011 data were compiled from a high-density multibeam hydrographic survey. The 2024 data were obtained by the manual digitization of Nautical Chart No. 204 (1:80,000 scale), following Mendes, El Robrini e Moraes (2022). A boundary polygon was created in QGIS to define the study area and ensure that the analyses were restricted to the area of the channel. In both datasets, the depths were normalized to the same vertical datum, that is, the Chart Datum (CD) or hydrographic zero adopted by the Brazilian Navy's Hydrography Directorate (DHN), to ensure altimetric comparability (Table 1).

Table 1 – The metadata, standardization parameters, and validation of the results of the 2011 and 2024 geostatistical models. The operational comparability of the two datasets was ensured by standardizing the parameters marked with an asterisk (*).

Parameter	2011 Data	2024 Data
Original Source	Multibeam Hydrographic Survey	Digitization of Nautical Chart No. 204
Point Density (n)	215,307 (High)	698 (Low)
Vertical Datum*	Reduction Level (NR) - DHN	Reduction Level (NR) - DHN
Horizontal Reference (CRS)*	SIRGAS 2000 / UTM Zone 22S (EPSG:31982)	SIRGAS 2000 / UTM Zone 22S (EPSG:31982)
Interpolation Method*	Ordinary Kriging	Ordinary Kriging
Variogram Model	Gaussian	Gaussian
Model Parameters	Nugget: 20 m ² , P. Sill: 50 m ² , Range: 5000 m	Nugget: 36.5 m ² , P. Sill: 68.3 m ² , Range: 3870 m
Search Parameters*	Radius: 22,500 m, 4 Sectors, Min 8, Max 64	Radius: 22,500 m, 4 Sectors, Min 8, Max 64
Final Grid Geometry*	Identical (Standardized)	Identical (Standardized)
Uncertainty (RMSE)	1.16 m	5.25 m

Source: the authors

As the two datasets were derived from sources with intrinsically different metadata and accuracy, a rigorous standardization process was implemented to ensure the validity of the comparative analysis.

Comparability was ensured through three steps: (1) the vertical standardization (Chart Datum) mentioned above; (2) geospatial metric standardization, which reprojected both datasets (2011 and 2024) and the boundary polygon onto the SIRGAS 2000 / UTM Zone 22S projected coordinate system (EPSG:31982), and (3) grid geometry standardization, which configured the 2011 grid was to have exactly the same extension, alignment, and resolution as the 2024 grid. This UTM standardization is the key step here, given that it converts degree-based coordinates into meters, thus enabling a uniform geostatistical analysis and the correct application of metric search radii.

Continuous bathymetric grids were generated for 2011 and 2024 in the Surfer software using ordinary kriging interpolation. For each dataset, a variogram model was fitted individually to reflect its spatial structure: for the 2011 data, a Gaussian model was fitted with a Nugget of 20 m², Partial Sill of 50 m², and Range of 5000 m, while for the 2024 data, a Gaussian model was fitted with a Nugget of 36.5 m², Partial Sill of 68.3 m², and Range of 3870 m. The kriging parameters were standardized for both models, using a 22,500 m search radius divided into four sectors, with a minimum of eight and a maximum of 64 points per estimate (Plant; Holland; Puleo, 2002).

The performance and reliability of each model were evaluated using leave-one-out cross-validation approach, quantified by the Root Mean Square Error (RMSE). The comparative morphodynamic analysis was conducted by generating four principal cartographic products, which were finalized in QGIS (Figure 2): (1) individual isobath maps for 2011 and 2024; (2) a difference map, which was obtained by subtracting the 2011 grid from the 2024 grid to visualize the areas of accretion (positive values) and erosion (negative values); (3) comparative cross-channel bathymetric profiles, and (4) maps of the depth gradient.

The chart datum was used as the reference for the calibration of the depths used in the present study. This datum is the vertical reference adopted by the Brazilian Navy's Hydrography and Navigation Directorate (DHN) to produce official nautical charts, including Nautical Chart no. 204. The chart datum is also referred to as hydrographic zero, and corresponds to the lowest astronomical tide (spring) predicted for the region, which is defined based on the statistical analysis of a long-term tide-gauge time series (Borba, 2020).

The 2011 bathymetric data and the values extracted from the 2024 nautical chart were interpolated using kriging, which was chosen due to its high level of accuracy for the modeling of bathymetric surfaces. An exploratory analysis of the data guided the adjustment of the interpolation parameters, considering their spatial variability and point distribution. The surfaces generated were validated by comparing the interpolated models with the control points available for the study region.

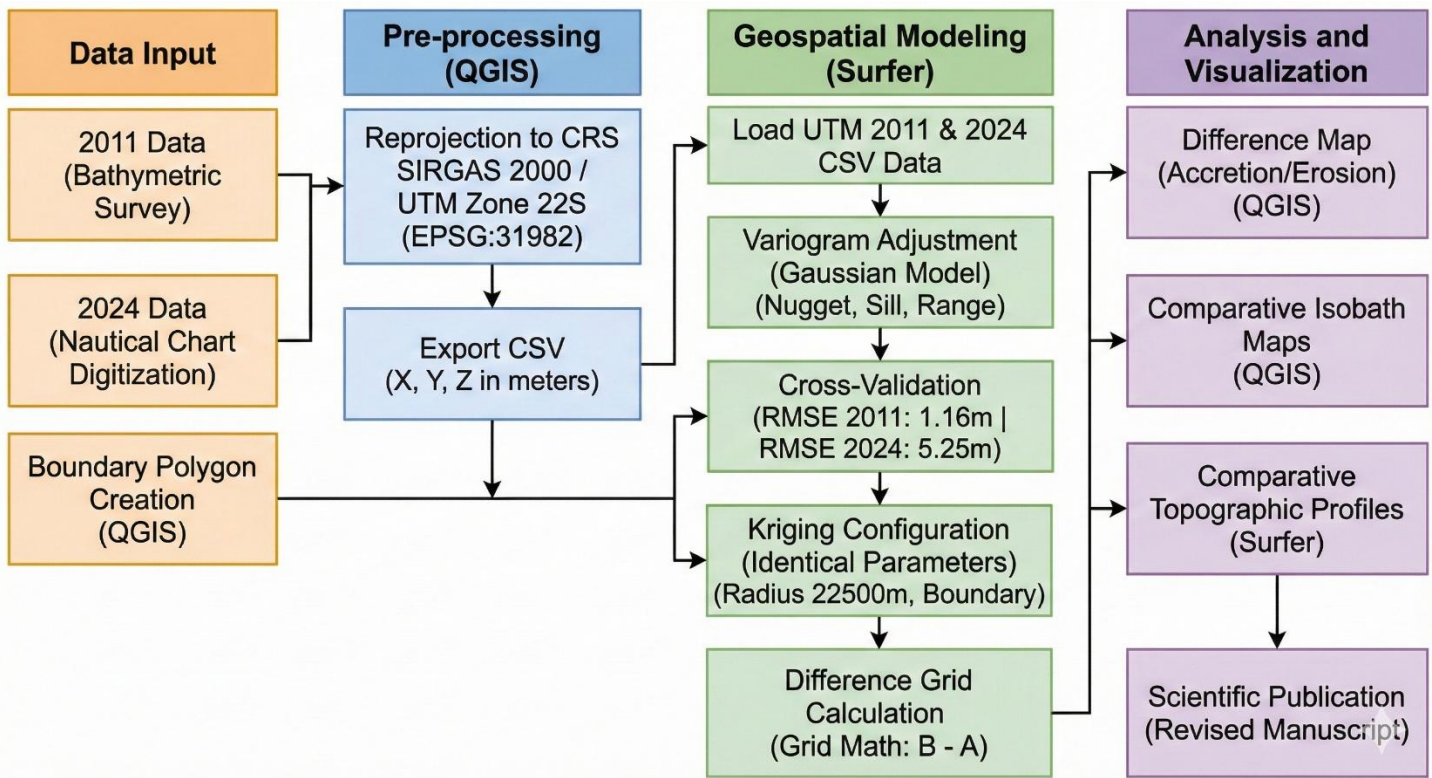


Figure 2 – Methodological flowchart of the present study, showing its four principal steps: (1) Data Input (2011 bathymetric survey, digitization of 2024 nautical chart, creation of boundary polygon); (2) Preprocessing in QGIS, including the crucial standardization of all data to SIRGAS 2000 / UTM Zone 22S (EPSG:31982); (3) Geospatial modeling and validation (Kriging) in Surfer, and (4) Analysis and visualization of the results (difference maps, profiles, and isobaths). Source: the authors.

Based on the interpolated surfaces, contour maps were produced to visualize the geomorphology of the channel, in an approach similar to that used by Gualtieri et al. (2018). Cross-sections were extracted at strategic locations along the channel to evaluate the variation in the depth and width of the navigation channel.

Gradient plots of the interpolated surfaces were also created, to provide a more detailed analysis of the geomorphological changes and to highlight the processes of erosion, deposition, and migration of the sandbanks. Six transverse profiles were distributed along the North Channel of the Amazon River to analyze the bathymetric migration of the channel (Figure 3). These profiles were derived from detailed bathymetric maps, spanning the full width of the channel, and are arranged in a parallel formation to provide a comprehensive view of the bathymetric variation.

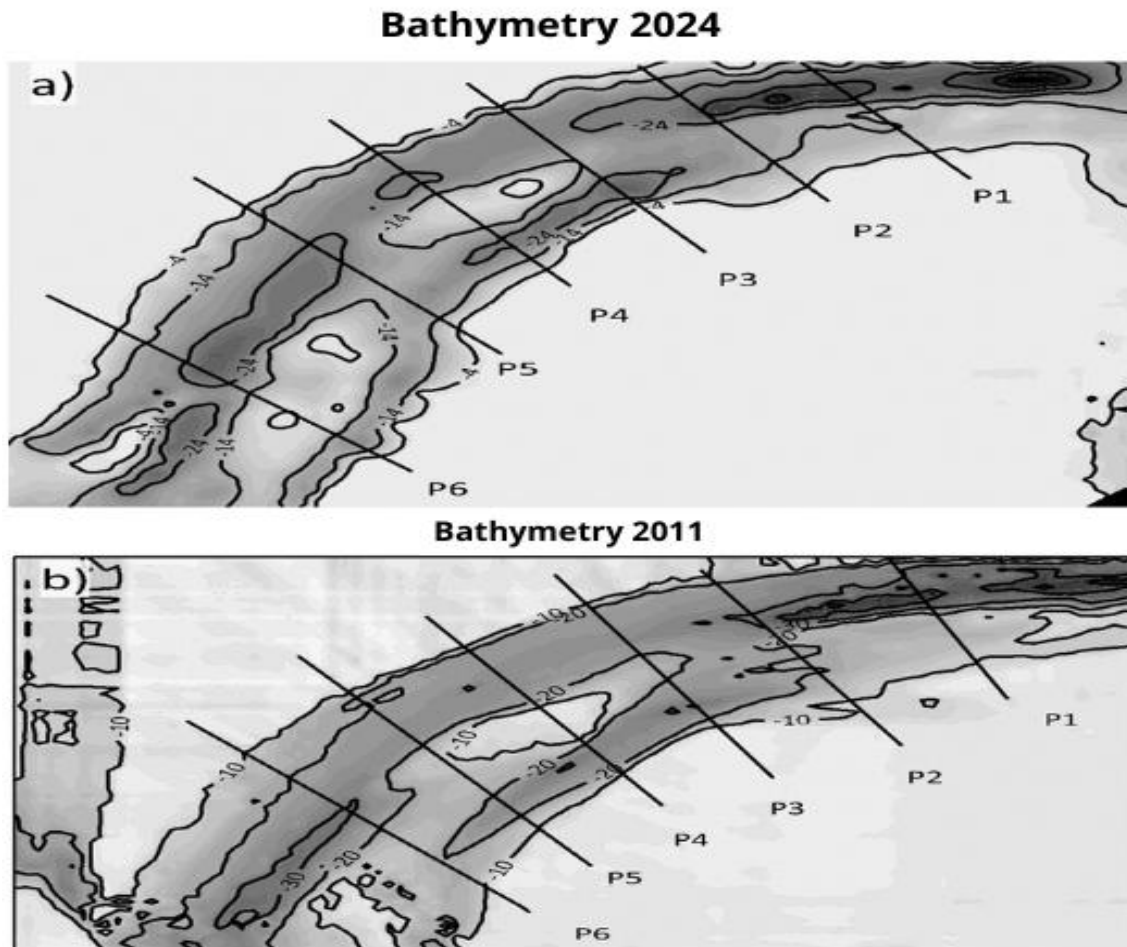


Figure 3 – Cross-channel bathymetric profiles (P1–P6) of the North Channel of the Amazon River: (a) 2024; (b) 2011. Source: the authors.

Each profile provides a representation of the underwater topography of the channel, which facilitates the identification of the migration, erosion, and sedimentation patterns that underpin the dynamics of the system (Rademann et al., 2023). The analysis of these profiles provides a more precise understanding of the shifts in subsurface features and the configuration of the riverbed, which may be associated with phenomena such as the alterations in hydrodynamic flow influenced by extreme climatic events (Queiroz; Marinho, 2024).

This vertical reference aims primarily to ensure navigational safety by guaranteeing that the depths shown on the charts correspond to the lowest possible values, even during the most extreme low tides (Santana et al., 2020). In this case, operating with data cross-referenced to the chart datum will ensure that the actual depth at a given location will rarely be lower than the value represented on the chart.

III. RESULTS AND DISCUSSION

Bathymetric Characteristics and Temporal Evolution of the North Channel

The first step in the present analysis is the assessment of the performance and uncertainty of the bathymetric models generated from the data. The rigorous cross-validation of the new geostatistical models, now in metric coordinates, revealed a substantial improvement in accuracy and, crucially, permitted the quantification of the uncertainty associated with each data source. The 2011 model, based on a high-density multibeam survey, proved to be extremely accurate, with a Root Mean Square Error (RMSE) of just 1.16 m. By contrast, the 2024 model, obtained by digitizing the nautical chart, returned a much higher RMSE, of 5.25 m. This difference in uncertainty (1.16 m vs. 5.25 m) is not a modeling flaw, but rather, a quantifiable outcome of the varying precision between a direct survey (2011) and the interpretation of a cartographic source (2024). The bathymetric maps for 2011 (Figure 4) and 2024 (Figure 5) reveal significant shifts in the geomorphology of the North Channel of the Amazon River. In 2011, maximum depths up to 50 m were observed near the outlet of the channel (Figure 4).

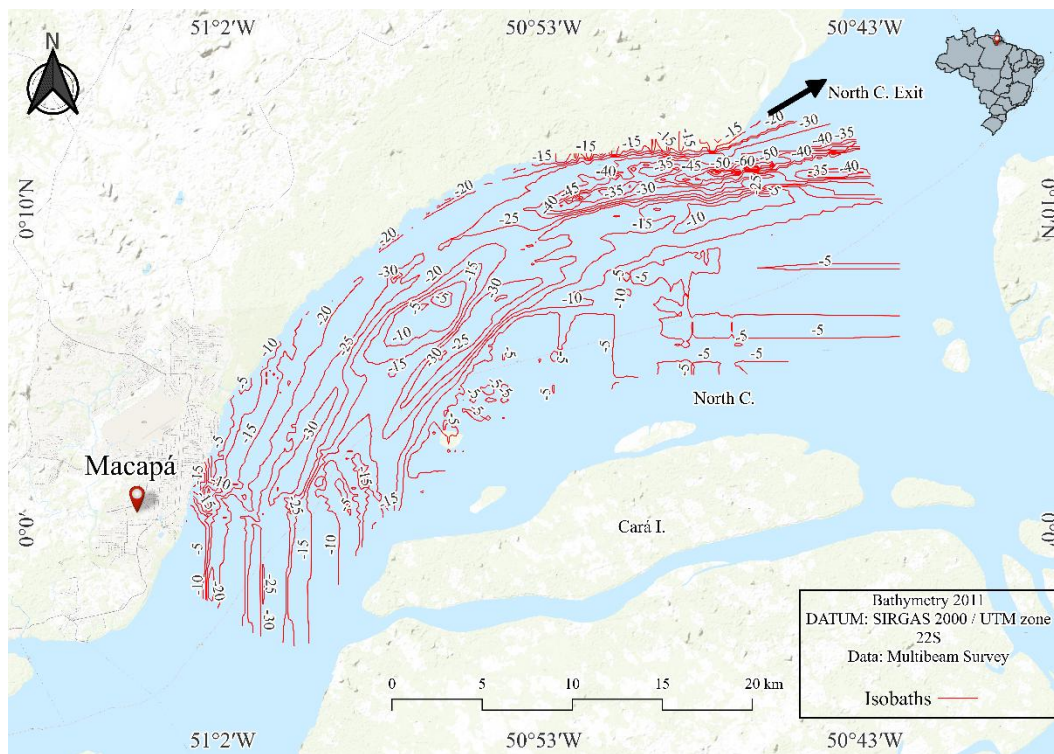


Figure 4 – Isobaths extracted from the 2011 hydrographic survey, bathymetry in XYZ. Source: the authors.

The sandbanks separating the primary and secondary channels were of between 10 and 15 m in height, which is consistent with the geomorphological compartmentalization of the area. On the western margin (near Macapá), the depth of the channel increased abruptly from 0 m at the shore to up to 24 m in the main channel.

The temporal analysis shows that the mean depth of the navigation channel decreased from 26 m in 2011 to 22 m in 2024, indicating a tendency for siltation. This process is consistent with the observations of

Herrero et al. (2018), who associate the declining mean depth of the channel with the continuous input of sediments modulated by the discharge of the river and the local tides. In 2024, the maximum depth of the channel was 45 m, while sandbanks extended to between 15 and 20 m, reflecting the migration and reconfiguration of the sedimentary features (Figure 5).

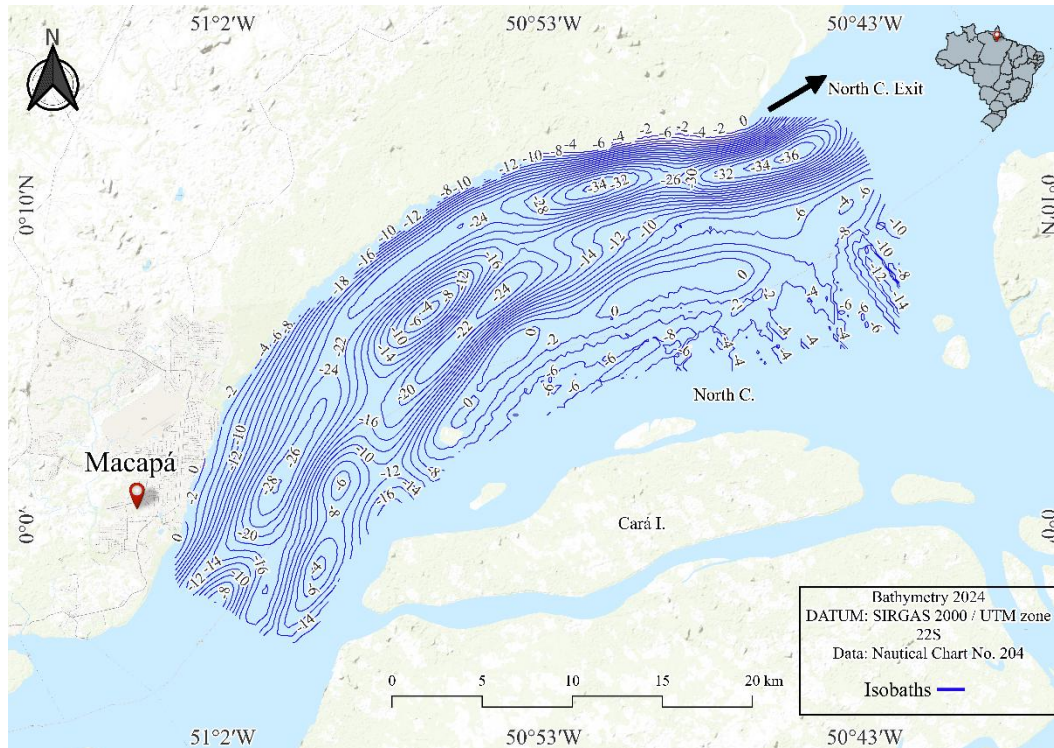


Figure 5 – Isobaths extracted from the 2024 bathymetry generated from nautical chart no. 204. Source: the authors.

Influence of the Tidal Regime and Hydrodynamic Processes

The tidal time series (Figure 6) indicates a semidiurnal macrotidal regime, with amplitudes exceeding 5 m and a mean of 2.79 m for the 2010–2022 period as a whole. This considerable amplitude modulates sediment transport, alternately promoting the resuspension and deposition of the sediments. Environments that have a large tidal amplitude tend to be subject to the intense redistribution of sediments (Sukhodolov et al., 2017; Khojasteh et al., 2021), which can drive the migration of the banks and modify the depth of the main channel.

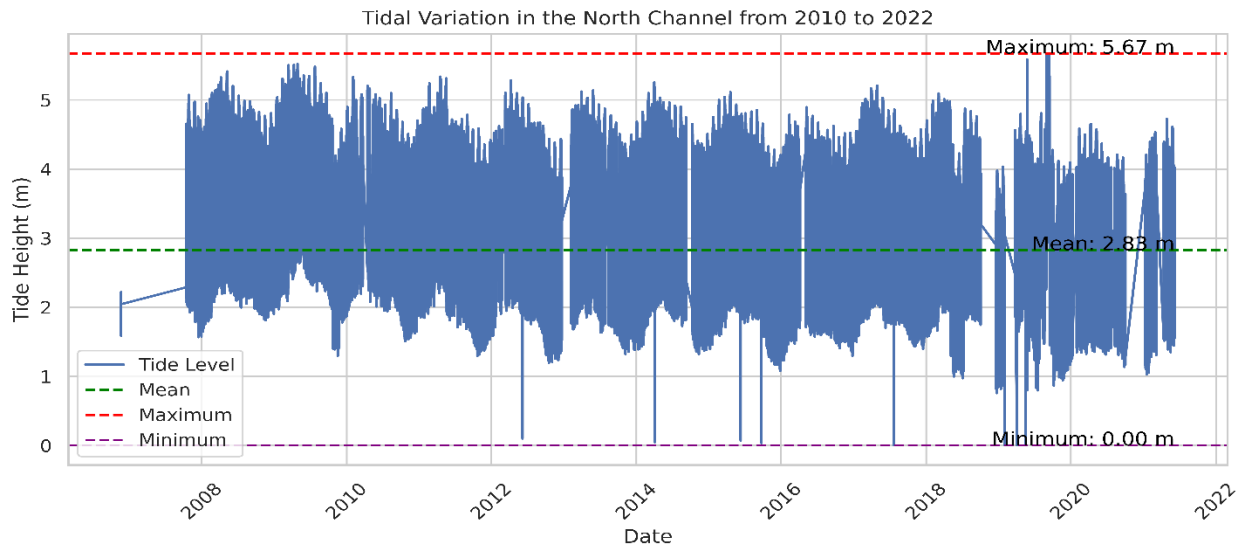


Figure 6 – Tidal time series recorded at the Macapá station for the period between 2010 and 2022, showing the maximum, minimum, and mean tide heights. Source: the authors.

Representation and Geomorphological Compartmentalization

The 2024 bathymetric modeling highlights a clear pattern of compartmentalization between the main channel (which has a mean depth of 26 m) and a secondary channel (depths of up to 6 m) located to the east, near Cará Island (Figure 7). This geomorphological differentiation can be counted for by the variation in the hydrodynamic energy regime, which is common in tidal channels with multiple bifurcations (Finotello et al., 2020).

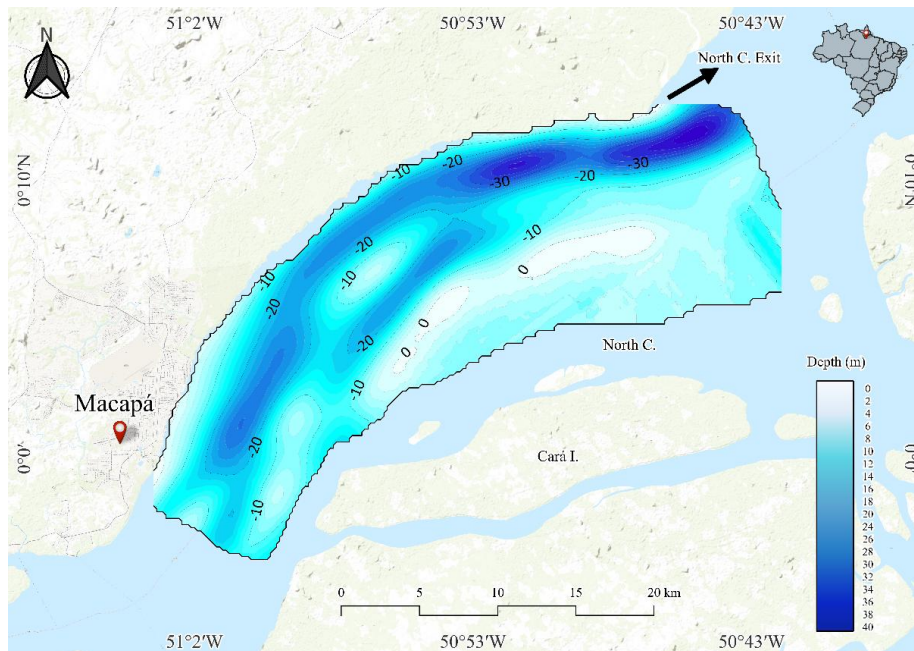


Figure 7 – The depth gradient map for the 2024 data generated from the bathymetric contours. Source: the authors

By contrast, the 2011 model presents more homogeneous features, in particular, a central subaqueous dune (Figure 8), which is indicative of a prior phase of either greater sedimentary equilibrium or reduced energy. The homogeneity of the channel bed may reflect either more stable hydrodynamic conditions or a reduced intensity of erosive processes (Barros; Rollnic; Watanabe, 2017). Previous studies Macapá Bay have shown that the variation in the geomorphology of the seabed is influenced by the constant action of hydrodynamic and sedimentary processes, which corroborates the link between surface features and subsurface structures (Almeida et al., 2024; Herrero et al., 2016).

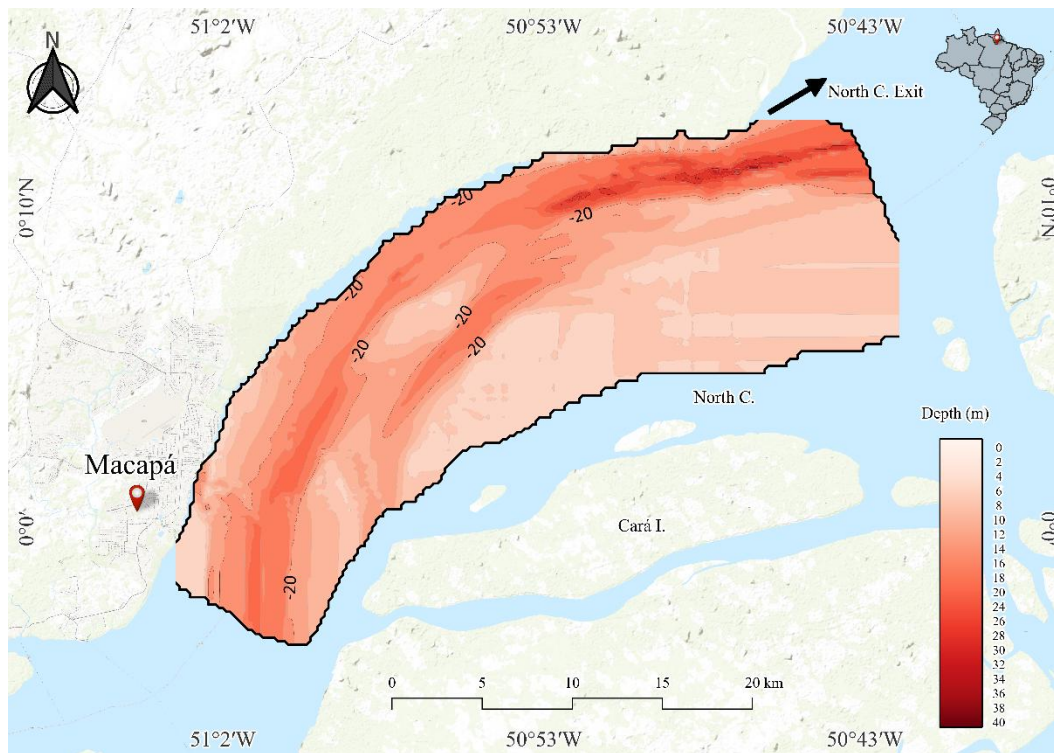


Figure 8 – The depth gradient map for 2011 generated from the isobaths. Source: the authors

The presence of subaqueous dunes is associated with sediment dynamics and hydrodynamic conditions. The interaction between the tides and the seasonal variation in the river input contributes to the redistribution of the sediments, which favors the formation of mobile sandbanks and shifts in the alignment of the secondary channels (Ahmed; Constantine; Dunne, 2019).

Migration of the Channel and Erosive–Depositional Processes

The comparison of the 2011 and 2024 grids (Figure 9) reveals the migration of the channel toward the east–northeast, with erosion occurring on the left margin and deposition on the right margin. This is consistent

with the patterns observed in large tropical rivers, where the interaction among the river discharge, tides, and sedimentation generates lateral shifts in the configuration of the channel (Fryirs, 2016; Franzinelli, 2011).

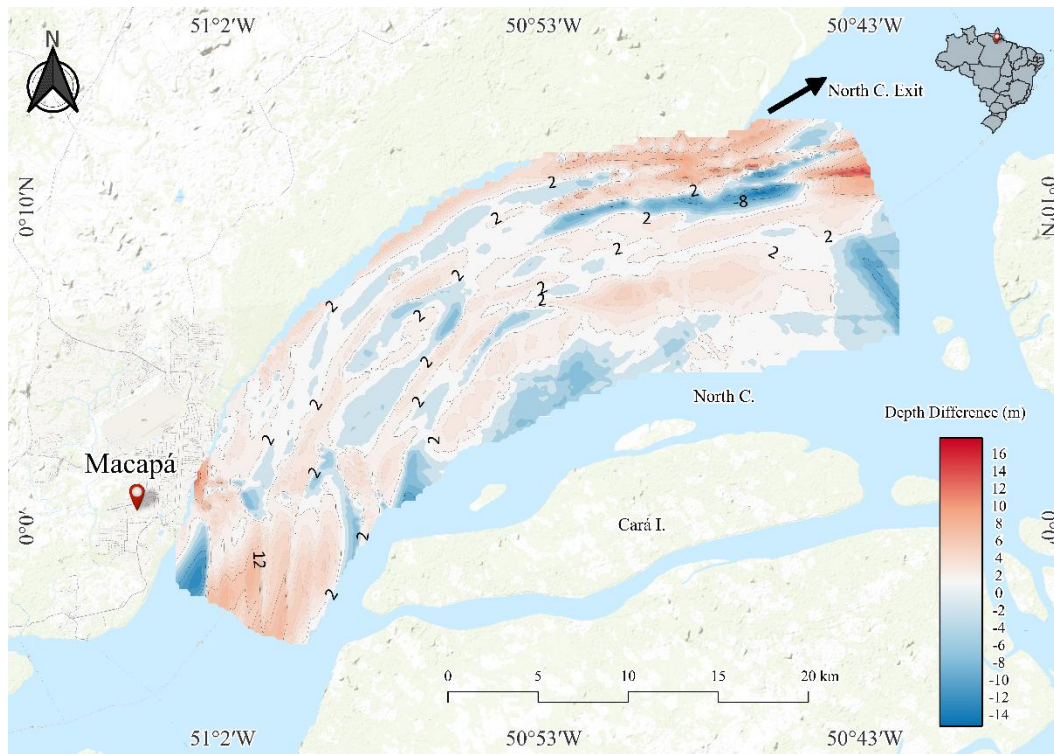


Figure 9 – Bathymetric difference map for the North Channel of the Amazon River (2011 vs. 2024). This map was produced by subtracting the 2011 grid from the 2024 grid (Grid₂₀₂₄ – Grid₂₀₁₁). The warm colors (red/orange) represent positive values, and indicate areas of accretion (decreasing depth), while the cool colors (blue) represent negative values, indicating areas of erosion (increasing depth). White (0) indicates areas of minimal or no change. Source: the authors.

The depth at the channel outlet increased from 50 m to 56 m between the two study years, indicating localized erosion. Marinho et al. (2022) relate this type of channel deepening to flow convergence and the combined action of fluvial and marine currents. Studies of the confluence of the Negro and Solimões rivers indicate that shifts in flow patterns, combined with movements of the bedload, can transform the geomorphology of the channel, including the formation of scour-like depressions and bar-shaped deposits (Jesus et al., 2024).

Analysis of the Cross-Channel Bathymetric Profiles

The cross-sections of the channel (Figure 10) reveal substantial changes in channel depth and width over the course of the present study period. In profiles 1 and 2, depth increased, combined with lateral expansion, which indicates the simultaneous erosion of both the bed and the margins. Profiles 4–6 reveal a reduction in depth, combined with increased width, which is consistent with bed sedimentation and lateral erosion, a

process observed frequently in channels undergoing geomorphological transition (Silva; Rabelo; Nunes, 2024; Sulaiman et al., 2021).

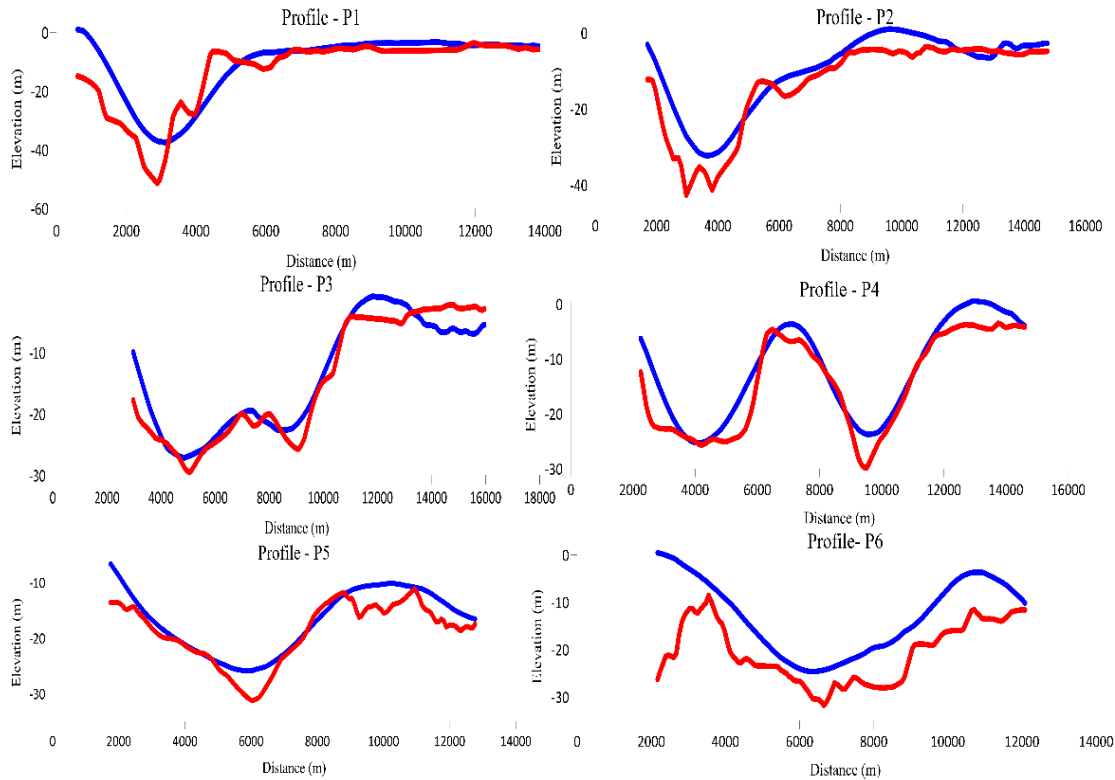


Figure 10 – Comparison of the bathymetric profiles (2011 - red vs. 2024 - blue) of the North Channel of the Amazon River. The plots show the variation in depth (vertical axis, in m) across the horizontal dimension (horizontal axis, in m) in profiles 1 to 6 (P1—P6).

While the depth of profile 3 remained stable, the channel widened from 500 m to 2000 m, which appears to reflect a process of vertical deposition offsetting the deepening of the channel (Figure 10). This type of redistribution is typical of fluvial systems influenced by marine intrusions (Gugliotta et al., 2018).

These findings reveal a dynamic system subject to frequent morphological shifts. The presence of secondary channels, sandbars, and submerged dunes reinforces the multichannel character of the sector, which is consistent with low-latitude, tide-dominated deltaic environments (Nittrouer et al., 2021).

Implications for Navigation and Port Management

The bathymetric and sedimentary dynamics of the North Channel pose a major challenge for regional shipping. The reduction of the depth of the channel in certain stretches can compromise the safety of shipping,

requiring frequent dredging, which incurs high costs and produces environmental impacts (Latrubesse et al., 2017).

As an alternative, navigation over fluid mud has been employed in some coastal port environments, such as that of Rotterdam in Holland, enabling safe operations even with drafts that exceed traditional proportions (Winterwerp; Wang, 2013; McAnally; Mehta, 2002). In fact, the adoption of dynamic draft management systems, like those that have already been implemented in many European ports, may be a viable strategy in the Amazon region (Xue et al., 2019).

The integration of bathymetric monitoring systems, numerical modeling, and adaptive operational strategies would thus promote efficient operations and the safety of navigation on Amazonian waterways (Ávila; Gallo, 2021). The difficulties of producing a high-precision model, as demonstrated in the present study, reinforce emphatically the need to invest in more frequent and concentrated bathymetric monitoring to improve both efficiency and safety in the complex management of Amazonian waterways.

IV. CONCLUSIONS

The analysis of the geomorphological evolution of the North Channel of the Amazon River between 2011 and 2024 revealed clear patterns of active morphosedimentary dynamics. The study identified an overall siltation process, with an overall reduction in the mean depth of the channel from 26 m to 22 m, which is consistent with its lateral migration toward the east–northeast.

A comparative analysis of the spacing between the isobaths of the two study years indicates an apparent displacement that, in some stretches of the channel, was of the order of 50 m over the 13-year period. However, the principal methodological contribution of the present study was the application of a robust geostatistical workflow in metric UTM coordinates, which not only permitted the modeling of the changes, but also the quantification of the differential uncertainty of the data sources. The validation revealed a high level of accuracy for the 2011 model (RMSE = 1.16 m) and a moderate level of uncertainty for the 2024 model (RMSE = 5.25 m).

Given this, it was possible to present the analyses of aggradation and migration with a known level of statistical confidence. The definition of a specific level of uncertainty further strengthens the conclusion that continuous bathymetric monitoring is an indispensable management tool for the region. The acknowledgment of this uncertainty thus reinforces the conclusion that continuous bathymetric monitoring is an indispensable navigational management tool for the region.

Navigational safety, and the optimization of costly maintenance strategies such as dredging, cannot be planned adequately on the basis of static representations of the channel bed. Understanding that bathymetric models are approximations with a quantifiable level of error is essential for the planning of safe shipping routes, ensuring access to the Santana shipping complex, and the development of sustainable river management policies.

Given this scenario, the adoption of innovative technological solutions, such as navigation over fluid mud and, in particular, the use of dynamic draft management, appears to represent the most promising alternative for coping with marked geomorphological variability observed in the North Channel of the Amazon River. Strategies of this type, which incorporate real-time data in the management of risks, are a direct response to the challenge posed by high levels of uncertainty. In this context, the present study highlights the strategic role of bathymetric analyses, not only for the understanding of the dynamics of major rivers, but also as a means of quantifying the uncertainties inherent to the measurement of these processes. This approach provides a sound baseline for the formulation of more realistic and safer technical guidelines for inland waterway transport management.

V. REFERENCES

- AGÊNCIA NACIONAL DOS TRANSPORTES AQUAVIÁRIOS. Estatístico Aquaviário 2023. Available at: <<https://web3.antaq.gov.br/ea/sense/transptku.html#pt>>. Accessed on: October 8, 2024.
- AHMED, J.; CONSTANTINE, J. A.; DUNNE, T. The role of sediment supply in the adjustment of channel sinuosity across the Amazon Basin. *Geology*, June 19, 2019.
- ALMEIDA, R. P. et al. Morphodynamics and depositional architecture of mid-channel bars in large Amazonian rivers. *Sedimentology*, March 12, 2024.
- ANTHONY, E. J. et al. The Amazon-influenced muddy coast of South America: A review of mud-bank–shoreline interactions. *Earth-Science Reviews*, v. 103, n. 3-4, p. 99–121, December 2010.
- ÁVILA, B.; GALLO, M. N. Morphological behavior of the Magdalena River delta (Colombia) due to intra and interannual variations in river discharge. *Journal of South American Earth Sciences*, v. 108, p. 103215, June 2021.
- BARROS, M. V. DA S.; ROLLNIC, M.; WATANABE, F. K. Caracterização das Principais Feições Superficiais de Fundo e Em Subsuperfície No Limite Sudoeste da Baía de Macapá, Canal do Norte, Rio Amazonas. *Tropical Oceanography*, v. 45, n. 1, 7 May 2017.
- BORBA, C. H. DE O. Compatibilização do Datum Vertical das Cartas Náuticas e Cartas Terrestres. *Anais Hidrográficos*, v. XIII, 2020.
- BRÊDA, J. P. L. F. et al. Climate change impacts on South American water balance from a continental-scale hydrological model driven by CMIP5 projections. *Climatic change*, v. 159, n. 4, p. 503–522, January 30, 2020.

BRODIE, K. L. et al. Simultaneous Mapping of Coastal Topography and Bathymetry From a Lightweight Multicamera UAS. *IEEE Transactions on Geoscience and Remote Sensing*, v. 57, n. 9, p. 6844–6864, September 2019.

CENTRO DE HIDROGRAFIA DA MARINHA. Tábuas de Maré | Centro de Hidrografia da Marinha. Available at: <<https://www.marinha.mil.br/chm/tabuas-de-mare>>. 2025.

COMPANHIA DAS DOCAS DE SANTANA. Programação de Navios. Available at: <<http://www.docasdesantana.com.br/index.php/operacional/programacao-de-navios>>. Accessed on: September 30, 2024.

CONSTANTINE, J. A. et al. Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin. *Nature Geoscience*, v. 7, n. 12, p. 899–903, November 2, 2014.

DIAS, L. C. et al. Análise da Tendência de Séries Históricas de Vazão na Bacia Hidrográfica do Rio Amazonas. *Revista AIDIS de Ingeniería y Ciencias Ambientales Investigación desarrollo y práctica*, p. 154–175, April 6, 2023.

DOUCETTE, P. et al. Error estimation for gridded bathymetry. *Zenodo (CERN European Organization for Nuclear Research)*, p. 1–20, October 1, 2015.

FAGUNDES, H. O. et al. Sediment Flows in South America Supported by Daily Hydrologic-Hydrodynamic Modeling. *Water Resources Research*, v. 57, n. 2, February 1, 2021.

FASSONI-ANDRADE, A. C. et al. High-resolution mapping of floodplain topography from space: A case study in the Amazon. *Remote Sensing of Environment*, v. 251, p. 112065–112065, September 11, 2020.

FASSONI-ANDRADE, A. C. et al. Seasonal to interannual variability of the tide in the Amazon estuary. *Continental shelf research*, v. 255, p. 104945–104945, February 1, 2023.

FINOTELLO, A. et al. Remotely-sensed planform morphologies reveal fluvial and tidal nature of meandering channels. *Scientific Reports*, v. 10, n. 1, January 9, 2020.

FRANZINELLI, E. Características morfológicas da confluência dos rios Negro e Solimões (Amazonas, Brasil). *Revista Brasileira de Geociências*, v. 41, n. 4, p. 587–596, December 1, 2011.

FRYIRS, K. A. River sensitivity: a lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms*, v. 42, n. 1, p. 55–70, April 22, 2016.

GALINDO, A. G. et al. O porto de Santana no estado Amapá como canal para o desenvolvimento do comércio internacional na Amazônia. *Revista Científica Multidisciplinar do CEAP*, v. 3, n. 1, p. 6–6, August 27, 2021.

GETIRANA, A. C. V.; PAIVA, R. C. D. Mapping large-scale river flow hydraulics in the Amazon Basin. *Water Resources Research*, v. 49, n. 5, p. 2437–2445, May 2013.

GUALTIERI, C. et al. A field study of the confluence between Negro and Solimões Rivers. Part 1: Hydrodynamics and sediment transport. *Comptes Rendus Geoscience*, v. 350, n. 1-2, p. 31–42, January 2018.

GUGLIOTTA, M. et al. Sediment distribution and depositional processes along the fluvial to marine transition zone of the Mekong River delta, Vietnam. *Sedimentology*, v. 66, n. 1, p. 146–164, August 9, 2018.

HERRERO, H. et al. Flow structure at a confluence: experimental data and the bluff body analogy. *Journal of Hydraulic Research*, v. 54, n. 3, p. 263–274, April 11, 2016.

HERRERO, H. et al. The influence of tributary flow density differences on the hydrodynamic behavior of a

- confluent meander bend and implications for flow mixing. *Geomorphology*, v. 304, p. 99–112, March 1, 2018.
- HOITINK, A. J. F.; JAY, D. A. Tidal river dynamics: Implications for deltas. *Reviews of Geophysics*, v. 54, n. 1, p. 240–272, March 2016.
- JESUS, J. et al. Caracterização Multitemporal de Barras Fluviais no Arquipélago de Mariuá, Médio Rio NPegro, AMAZONAS. *Revista Geonorte*, v. 15, n. 48, February 9, 2024.
- JO, H.; PYRCZ, M. J. Automatic Semivariogram Modeling by Convolutional Neural Network. *Mathematical Geosciences*, v. 54, n. 1, p. 177–205, July 12, 2021.
- KHOJASTEH, D. et al. Sea level rise impacts on estuarine dynamics: A review. *Science of The Total Environment*, v. 780, p. 146470, August 2021.
- KOSUTH, P.; CALLÈDE, J.; LARAQUE, A. Ocean Tide Waves Propagation along Downstream Amazon River: Measuring the Amazon Discharge at the Estuary. *Proceedings*, September 11, 2000.
- LATRUBESSE, E. M. et al. Damming the rivers of the Amazon basin. *Nature*, v. 546, n. 7658, p. 363–369, June 1, 2017.
- LEWIS, Q. W.; RHOADS, B. L. Rates and patterns of thermal mixing at a small stream confluence under variable incoming flow conditions. *Hydrological Processes*, v. 29, n. 20, p. 4442–4456, May 22, 2015.
- MARINHO, R. R. et al. Riverbed morphology and hydrodynamics in the confluence of complex mega rivers - A study in the Branco and Negro rivers, Amazon basin. *Journal of South American Earth Sciences*, v. 118, p. 103969–103969, October 1, 2022.
- MCANALLY, W. H.; MEHTA, A. J. Significance of Aggregation of Fine Sediment Particles in Their Deposition. *Estuarine, Coastal and Shelf Science*, v. 54, n. 4, p. 643–653, April 2002.
- MENDES, C. A. C.; ROBRINI, M. E.; MORAES, H. B. DE . Dinâmica dos fundos das áreas de disposição de sedimentos dragados na Baía de Guajará, Pará, Brasil. *Revista Brasileira de Geomorfologia*, v. 23, n. 1, January 13, 2022.
- MILLIMAN, J. D.; FARNSWORTH, K. L. *River Discharge to the Coastal Ocean*. Cambridge University Press, 2011.
- NITTROUER, C. A. et al. Amazon Sediment Transport and Accumulation Along the Continuum of Mixed Fluvial and Marine Processes. *Annual Review of Marine Science*, v. 13, n. 1, p. 501–536, January 3, 2021.
- PLANT, N. G.; HOLLAND, K. TODD.; PULEO, J. A. Analysis of the scale of errors in nearshore bathymetric data. *Marine Geology*, v. 191, n. 1-2, p. 71–86, November 2002.
- QUEIROZ, M. S. DE; MARINHO, R. R. Rio Congo: Análise do Fluxo de Sedimentos Suspensos em uRam Megassistema Multicanal na África Central. *RAEGA - O Espaço Geográfico em Análise*, v. 61, p. 153–172, December 18, 2024.
- RADEMANN, L. K. et al. Avaliação da Dinâmica de Bancos de Areia Com Imagens De Alta Resolução No Rio Areal do Limeira, Sul do Brasil. *RAEGA - O Espaço Geográfico Em Análise*, v. 57, p. 3–3, September 12, 2023.
- RUDORFF, C. M.; MELACK, J. M.; BATES, P. D. Flooding dynamics on the lower Amazon floodplain: 2. Seasonal and interannual hydrological variability. *Water Resources Research*, v. 50, n. 1, p. 635–649, January 2014.
- SAMPAIO, R. S.; ROBRINI, M. E. Mudança de níveis de água (1995-2021) no Estuário Superior do rio Amazonas (Baixo Amazonas - Pará): possíveis fatores que afetam. *Revista Brasileira de Geografia Física*, v. 17, n. 2, p. 882–

894, March 14, 2024.

SANTANA, F. R. et al. Cartas Náuticas com Modelos SEP: Evolução Histórica, e Perspectivas para Hidrografia Brasileira. *Revista Brasileira de Cartografia*, v. 72, p. 1299–1328, December 30, 2020.

SANTOS, E. M. et al. Planejamento portuário: recomendações para acessos náuticos. 1. ed. Rio de Janeiro: Praticagem do Brasil, 2022.

SCHAEFFER, R. et al. A New Infrastructure For The Amazon. *The Amazon we want*, December 9, 2023.

SILVA, Á. S. DA; TOBIAS, M. S. G. A Viabilidade do Porto de Santana no Contexto do Projeto Arco Norte E Seus Condicionantes. *Editora Científica Digital eBooks*, p. 25–44, January 1, 2023.

SILVA, T. G. DA; RABELO, F. D. B.; NUNES, H. K. DE B. Geomorfologia fluvial e geodiversidade do Lago de Tefé (Tefé, Amazonas, Brasil). *Revista Brasileira de Geografia Física*, v. 17, n. 4, p. 2396–2411, July 23, 2024.

SUKHODOLOV, A. N. et al. Turbulent flow structure at a discordant river confluence: Asymmetric jet dynamics with implications for channel morphology. *Journal of Geophysical Research: Earth Surface*, v. 122, n. 6, p. 1278–1293, June 2017.

SULAIMAN, Z. A. et al. The Influence of Tides on Coastal Plain Channel Geomorphology: Altamaha River, Georgia, USA. *Journal of Geophysical Research Earth Surface*, v. 126, n. 7, June 13, 2021.

WINTERWERP, J. C.; WANG, Z. B. Man-induced regime shifts in small estuaries—I: theory. *Ocean Dynamics*, v. 63, n. 11-12, p. 1279–1292, November 12, 2013.

XUE, J. et al. Multi-attribute decision-making method for prioritizing maritime traffic safety influencing factors of autonomous ships' maneuvering decisions using grey and fuzzy theories. *Safety Science*, v. 120, p. 323–340, December 1, 2019.

ZANIN, P. R. et al. Streamflow Dynamics of Amazonian Rivers According to Their Hydrogeochemical Heterogeneity. *Heterogeneity*, January 1, 2024.
