XXVI SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

WATER AGE VARIABILITY IN THE AMAZON-PARÁ ESTUARINE SYSTEM

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Abstract: The water age method was applied to the Amazon and Pará Rivers to assess water exchange processes under seasonal variability: the wet season (April to August) and the dry season (September to January). A two-dimensional hydrodynamic model (SisBaHiA) was used and validated against field observations from the Belém Harbor station on the Guamá River. The model allowed for the numerical determination of the spatiotemporal distribution of water age based on hydrodynamic forcing. Results indicate that, during the wet season, mean water age values are approximately 5 days in the Pará River, 8 days in the North Channel, 9 days in the South Channel, and 22 days in Bocas Bay. In the dry season, these values increase to about 8, 17, 24, and 38 days, respectively. Lower water age values are associated with stronger fluvial discharge in the wet season, while higher values are linked to the reduced inflow during the dry season. Bocas Bay consistently shows the highest water age values, indicating poor water exchange and longer residence times.

Resumo: O método da idade da água foi aplicado aos rios Amazonas e Pará com o objetivo de investigar os processos de troca hídrica em função da sazonalidade da região: período chuvoso (abril a agosto) e período seco (setembro a janeiro). Utilizou-se o modelo hidrodinâmico bidimensional SisBAHIA, cujo desempenho foi validado com dados de campo obtidos na estação do Porto de Belém, no rio Guamá. Através da modelagem, determinou-se numericamente a distribuição espaço-temporal da idade da água em função das forçantes hidrodinâmicas. Os resultados indicam que, durante o período chuvoso, os valores médios de idade da água são de aproximadamente 5 dias no rio Pará, 8 dias no Canal Norte, 9 dias no Canal Sul e 22 dias na Baía das Bocas. Já no período seco, esses valores aumentam para 8, 17, 24 e 38 dias, respectivamente. Observa-se que os menores tempos de residência ocorrem durante o período chuvoso, em função da maior vazão fluvial, enquanto os maiores valores são verificados no período seco. A Baía das Bocas apresenta os maiores tempos de renovação, destacando-se como uma região de baixa troca hídrica.

Palavras-Chave – Estuários dos rios Amazonas e Pará, Idade da água, Modelagem hidrodinâmica

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INTRODUCTION

Water age (WA) is a widely used approach to quantify water renewal in semi-enclosed water bodies, such as bays and estuarine systems (Ren *et al*., 2014). Many estuarine environments worldwide are undergoing significant ecological degradation, including eutrophication and biogeochemical imbalances. According to Braunschweig *et al*. (2003), both pollutant inputs and water exchange rates play a critical role in determining estuarine water quality. Comparing WA with biogeochemical activity rates provides valuable insights into system dynamics. In estuaries, WA serves as an indicator of the residence time of biomass, nutrients, and contaminants under prevailing biochemical conditions, an essential aspect for understanding eutrophication processes. The complexity of water exchange in estuarine systems stems from the interplay of dynamic processes acting across multiple spatial and temporal scales.

Despite the growing use of water age modeling in various regions, few studies have focused on the Amazon-Pará estuarine system, a globally significant and complex hydrodynamic environment. Understanding WA dynamics in this context is critical, not only for advancing scientific knowledge but also for supporting environmental management efforts in this ecologically and socially strategic region of Brazil.

This study aims to evaluate the spatial variability of water age in the Amazon-Pará estuarine system. To this end, we implemented a WA modeling approach based on the two-dimensional hydrodynamic model SisBaHiA[1] (Base System for Environmental Hydrodynamics), developed by the Ocean Engineering Program at the Federal University of Rio de Janeiro. This modeling framework has demonstrated reliability in simulating circulation patterns in complex aquatic environments.

This paper is organized as follows: Section 2 describes the study area; Section 3 presents the materials and methods, including the modeling approach; Section 4 discusses the simulation results; and Section 5 summarizes the main findings and conclusions, highlighting their implications for estuarine management. Given the strategic importance of the Amazon-Pará estuarine system, understanding water age dynamics offers critical insights for sustainable management and mitigation of environmental impacts in one of the planet's most influential hydrological regions.

DESCRIPTION OF THE STUDY AREA

The study area extends between latitudes 3°S and 4°N and longitudes 56°W and 46°W (Figure 1a), encompassing the lower reaches of the Amazon and Pará Rivers, from their mouths to the city of Óbidos. This region includes extensive wetlands and estuarine zones, draining approximately 38,600 km². The Pará River originates in Bocas Bay and receives part of the Amazon River's discharge through the Breves and Boiuçu straits. Major tributaries within the study area include the Tapajós River, which contributes about 1% of the global freshwater discharge to the oceans (Freitas, 2017), the Xingu River, with a mean annual discharge of approximately 8,000 $m^3 \cdot s^{-1}$ and ranking as the fifth-largest tributary of the Amazon (Dias, 2015), and the Tocantins, Guamá, and Acará-Moju rivers. The Amazon and Pará Rivers are highly dynamic systems, with freshwater discharge and oceanic tides acting as the primary drivers of water level variability.

The Amazon River opens eastward in a wedge-shaped configuration and is divided into two main channels: the North channel and the South channel. These channels are separated by a series of islands and the Santa Rosa sandbank, a large shoal where extensive mudflats are exposed at low tide.

[1] http://www.sisbahia.coppe.ufrj.br

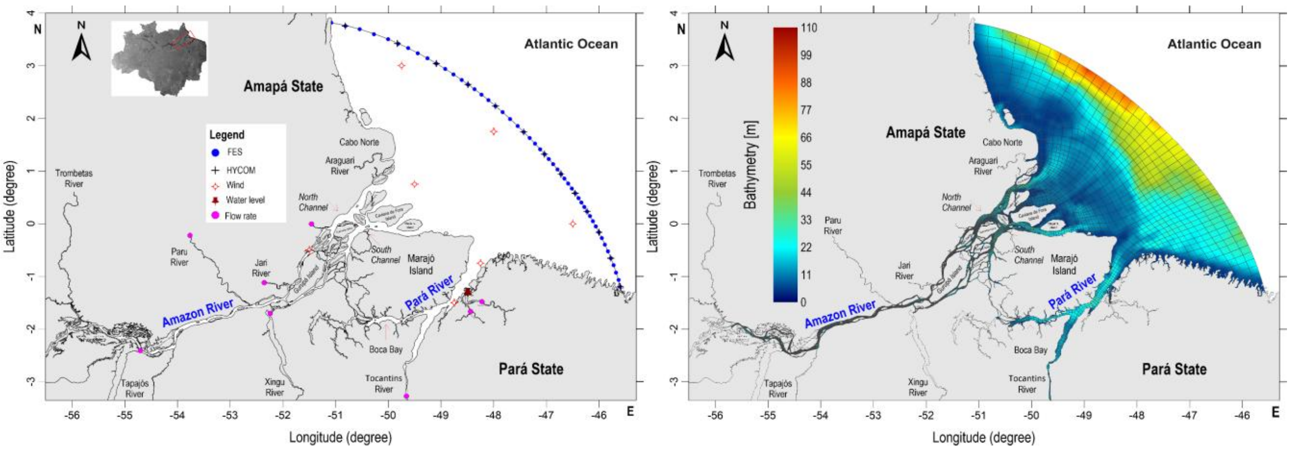
Both channels serve as the primary conduits for the entire Amazon River discharge, the largest freshwater discharge of any river in the world (Latrubesse, 2005; Goes, 2014).

Historically, the North Channel was considered to carry the greater portion of the discharge (Limeburner *et al*., 1995). However, more recent field data from the TROCAS project (Net Exchanges of the Lower Amazon River Ecosystem), collected between September 2010 and July 2012, indicate a shift: approximately 61% of the total discharge now flows through the South Channel and 39% through the North Channel near Macapá. These findings were consistent with earlier data from the HiBAm project (Hydrology of the Amazon Basin), measured in May 2000, and corroborated by Gabioux *et al*. (2005).

Both channels are nominally deeper than 10 m but are characterized by outer river mouth shoals with depths of approximately 6 m. The water discharge patterns are influenced not only by river flow but also by significant tidal forcing. According to Kosuth (2009), tidal propagation in the Amazon River can reach up to 800 km upstream, making the lower Amazon and its tributaries a vast tidal river system. The Amazon estuary is classified as macrotidal (Dyer, 1997), with tidal ranges between 4 and 6 m (Gallo, 2005). The semidiurnal M2 tidal constituent is a major driver of hydrodynamic circulation in the region (Gabioux *et al*., 2005), accounting for more than half of the total tidal elevation (Beardsley, 1995). Prestes *et al*. (2017) demonstrated that the M2 component also represents more than 40% of the total tidal energy in the Pará River estuary.

The estuarine area of the Pará River, characterized by a low topographic gradient and active sedimentation, contains bottom sediments composed primarily of fluid mud and mud mixed with sand in varying proportions, similar to those observed in the Amazon River estuary.

Figure 1 – Region of study: a) Map of the Amazon and Pará estuaries and location of the boundary conditions and data stations in the study area. b) Bathymetry and numerical mesh used in simulations.



MATERIALS AND METHODS

Hydrodynamic model

This study employed the depth-averaged module of the SisBaHiA hydrodynamic model (Rosman, 2025), whose governing equations are derived from the incompressible Navier-Stokes equations under the hydrostatic approximation. The adopted turbulence model is based on filtering techniques akin to the Large Eddy Simulation approach, using Gaussian filtering functions (Aldama, 1990; Galperin, 2010; Berselli, 2010). The shallow water equations, expressed in conventional indicial notation, account for horizontal velocity components, free surface elevation, Coriolis acceleration, gravitational acceleration, wind stress, bottom friction, and turbulent stress tensors.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial H u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -g \frac{\partial \zeta}{\partial x_i} - g \frac{H}{2} \frac{\partial \left(\frac{\rho}{\rho_r} \right)}{\partial x_i} + \frac{1}{H} \left[\frac{\partial}{\partial x_i} \left(H \frac{\tau_{ij}}{\rho_r} \right) \right] + \frac{1}{H} \left(\frac{\tau_i^s - \tau_i^b}{\rho_r} \right) + a_i \ , \tag{2}$$

To address the complex floodplain dynamics of the lower Amazon River, marked by numerous channels and lakes, we incorporated a wetting and drying algorithm developed by Barros *et al*. (2014), which accounts for moving boundaries in wetland regions.

Advection-diffusion equation

Water age (WA) was estimated through the release of a passive tracer with an initial concentration of 100%. The model simulates the temporal evolution of the tracer using the advection-diffusion equation, solved with an Eulerian approach.

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} = \frac{1}{H} \frac{\partial}{\partial x_j} \left(H \left[D_{ij} \delta_{ij} + \frac{\Lambda_k}{12} \left| \frac{\partial u_j}{\partial x_k} \right| \right] \frac{\partial C}{\partial x_k} \right) \tag{3}$$

Diffusion and dispersion coefficients (D_{ij}) in the x and y directions were based on values proposed by Bedford (1993) and Rosman (2001). Bottom fluxes were considered negligible.

Water age calculation

The WA calculation follows the methodology described in the SisBaHiA Technical Reference Manual[2]. WA corresponds to the elapsed time associated with the decay of a passive tracer, assumed to follow first-order kinetics. Considering a well-mixed water body with an initial concentration C_0, the concentration of the age-marker substance at time t, denoted by $C(t)$, evolves according to the following first-order decay equation:

$$\frac{dC}{dt} = -k_d C \tag{4}$$

Integrating this equation yields the expression:

$$C(t) = C_0 \exp^{(-kt)} \tag{5}$$

Where the elapsed time t (interpreted as the water age) is given by:

$$t = \frac{-\ln \left(\frac{C(t)}{C_0} \right)}{k} \tag{6}$$

This approach allows the estimation of how long water parcels have remained in the domain, based on the observed decay of the tracer concentration. The concept is analogous to that used in

[2] https://www.sisbahia.coppe.ufrj.br/assets/downloads/SisBaHiA_RefTec_v12b.pdf

radiocarbon dating, where the decay follows exponential kinetics characterized by parameters such as half-life T_{50} or order-of-magnitude life T_{90}.

In natural water bodies, where water inflows and outflows occur at multiple locations and times, and where concentration fields vary in space and time due to turbulent transport, the water age becomes a spatially and temporally distributed function. At each point, the WA represents the average age of the local water mixture composed of parcels with distinct histories. This can be mathematically expressed as:

$$WA(x,y,t) = \frac{-\ln\left(\frac{C(x,y,t)}{C_0}\right)}{k_d} = \ln\left(\frac{C}{C_0}\right)\frac{T_{50}}{\ln(0.5)} = \ln\left(\frac{C}{C_0}\right)\frac{T_{90}}{\ln(0.1)} \tag{7}$$

Although WA is theoretically independent of the decay constant k_d, small variations may arise due to the influence of concentration gradients on advective and diffusive fluxes. Thus, selecting an appropriate T_{90} value is critical for reliable WA estimation.

Implementation model

The computational domain spans approximately 169,406 km² (3°S to 4°N, 56°W to 46°W), discretized into 3,660 quadrilateral and 13 triangular elements, totaling 17,338 nodes. Mesh resolution varies from 14 km × 13 km near the oceanic boundary to 5 km × 3 km in the Amazon and Pará River channels to better capture local dynamics (Figure 1b).

Bathymetric data were sourced from nautical charts published by the Brazilian Navy's Hydrography and Navigation Directorate (DHN[3]), complemented by field data from Eastern Amazonian Waterways Administration (AHIMOR) and the Sediment Dynamics Laboratory (UFRJ). Open boundary water levels were forced using 18 tidal constituents (e.g., M2, S2, K1, O1), with amplitude and phase interpolated from the FES2014 global tide model. Horizontal velocities at the boundary were derived from the HYCOM[4] (Hybrid Coordinate Ocean Model) global ocean model.

Daily average discharges were imposed at fluvial boundaries of the Amazon, Tapajós, Xingu, Paru, Jari, and Tocantins Rivers. For the Guamá and Acará Rivers, discharges were estimated using the SWAT[5] (Soil & Water Assessment Tool) hydrological model (Arnold *et al.*, 1998). The model was calibrated using observed data from Brazilian National Water Agency (ANA) stations over the period 1983–2008, and validated for the period 2009–2018. This calibration and validation procedure ensured greater reliability in simulating the hydrological behavior of ungauged catchments. Based on data from 2020, the final simulations were adjusted to reflect current hydrological conditions. According to measurements from the TROCAS Project (May 2014), the discharge distribution in the Amazon River was set to 61% through the South Channel and 39% through the North Channel, near the city of Macapá. No inflows were imposed at the Trombetas and Jacaré Rivers.

Sediment types were defined according to classifications from Gabioux (2005), Gallo (2005), Arentz (2009), Gregório and Mendes (2009), and Teódulo (2017). Fine sand predominates in the Amazon River's upper and lower reaches; consolidated mud and sandbars occur near the mouths; and

[3] https://www.marinha.mil.br/chm/dados-do-segnav-cartas-nauticas
[4] https://www.hycom.org/data/glbu0pt08/expt-91pt2
[5] https://swat.tamu.edu/

mud, sand mixtures dominate the Guamá, Acará, and Pará Rivers. The Tocantins River consists primarily of sand.

Wind data (speed and direction) were extracted from ERA5 reanalysis (European Centre for Medium-Range Weather Forecast's - ECMWF), considering measurements at 10 m above surface, averaged for the period January–December 2020. Reanalysis data were used due to the limited availability of meteorological stations in the study area.

This methodological framework not only ensures robust simulation of hydrodynamic processes in a highly complex estuarine system, but also contributes to advancing the understanding of how water dynamics shape ecological, territorial, and social transformations in the Amazon region. By integrating multi-source data and adapting established models to the specific conditions of the Lower Amazon and Pará Rivers, the approach reinforces the importance of scientific knowledge as a tool for territorial governance, sustainable water management, and the connection between environmental processes and local realities.

RESULTS AND DISCUSSION

Water age

Water age (WA) is a fundamental timescale for characterizing water renewal and exchange processes in aquatic systems and is widely used to assess spatial variability in hydrodynamic connectivity (Ren *et al*., 2014). In this study, the two-dimensional hydrodynamic model was calibrated against observed water level data (Figure 2) and enhanced with a WA module to simulate freshwater age in the Amazon and Pará Rivers. To analyze the influence of seasonal hydrological regimes, two contrasting scenarios were defined:

- Scenario 1: High-water period (wet season, April–August)
- Scenario 2: Low-water period (dry season, September–January)

These periods reflect the pronounced seasonal variability in discharge patterns, which significantly modulate estuarine circulation, water renewal, and connectivity between riverine, wetland, and coastal systems. By evaluating WA under these conditions, we gain insight into how seasonal discharge fluctuations affect residence times and transport processes throughout the system.

The results reveal marked spatial and seasonal variability in water age (Figure 3). During the wet season, renewal times were shortest in the Pará River (~5 days), followed by the North Channel (~8 days), the South Channel (~10 days), and Bocas Bay (~22 days) (Figure 3a–b). In the dry season, water age increased significantly: ~8 days in the Pará River, ~17 days in the North Channel, ~24 days in the South Channel, and over 38 days in Bocas Bay (Figure 3c–d).

These differences are directly related to the reduction in river discharge during the dry season, which results in slower flushing rates, particularly in semi-enclosed areas such as Bocas Bay. There, residence time nearly doubled compared to high-water conditions. This sensitivity to seasonal inflow variation reinforces findings from other estuarine systems that exhibit strong coupling between discharge, renewal time, and water quality (e.g., Montagna *et al*., 2012; Delhez *et al*., 2004).

Figure 2 – Comparison between observed and simulated water elevations at Belém harbor station in October 2020.

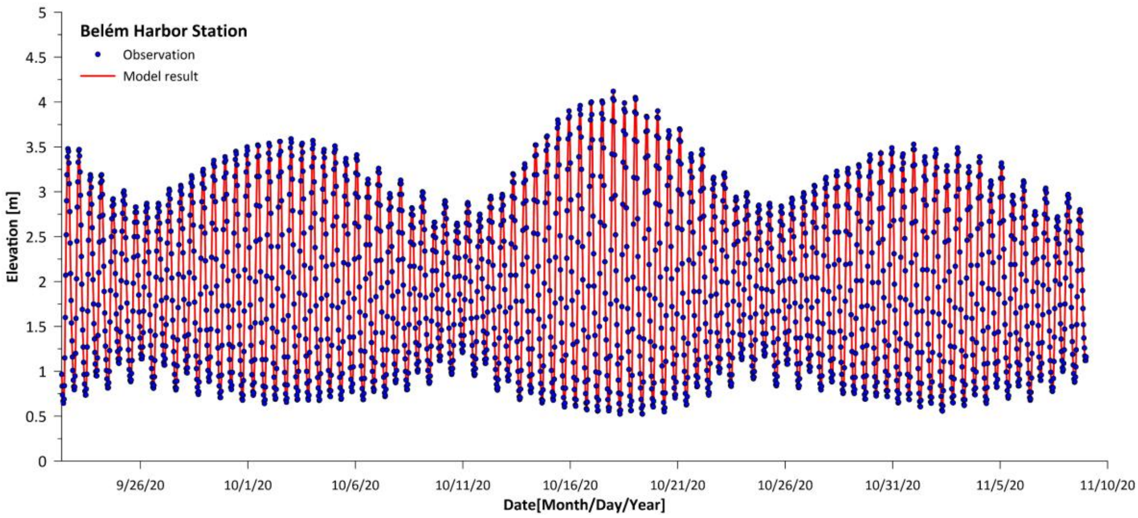
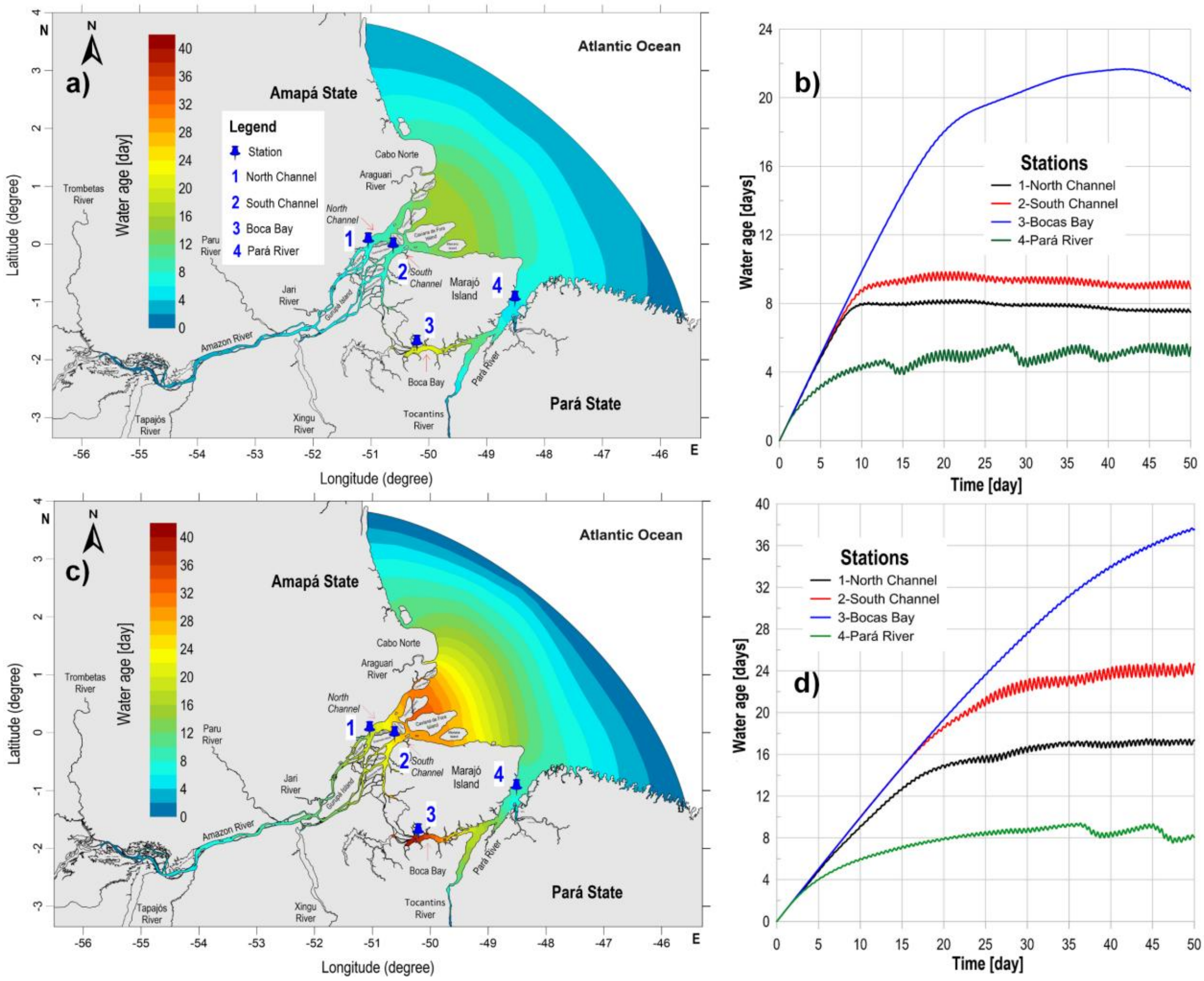


Figure 3 – Maps of isoline of WA distribution after 50 days of simulation for the wet (a) and dry (c) seasons. Time series of WA (for the wet (b) and dry (d) seasons) at four monitoring stations located in the estuaries of the Amazon River (North and South channels) and the Pará River (Bocas Bay and near the Pará River mouth).



The extended residence times during low-flow conditions may have important implications for estuarine ecology. Longer WA increases exposure to biogeochemical processes such as sedimentation, nutrient cycling, and oxygen depletion, which can exacerbate pollutant accumulation and hypoxia risk, especially in sheltered zones.

Additionally, the model's ability to reproduce observed water elevations at the Belém harbor station (Figure 2) demonstrates its robustness in capturing key hydrodynamic processes, lending credibility to the simulated WA fields.

Overall, these findings highlight how water discharge functions as a regulating force in estuarine dynamics, reinforcing the importance of understanding temporal and spatial patterns of water age in large-scale tropical systems. The results contribute to the broader discussion of water as a transformative agent in shaping ecological processes and human, environment interactions in the Amazon coastal region.

The results of this study demonstrate that water discharge acts as a key regulating force in the dynamics of estuarine systems, significantly influencing water renewal and residence times across different spatial and temporal scales. The simulated patterns of water age reveal how seasonal hydrological variability alters the circulation and flushing efficiency of the Amazon-Pará estuarine complex, especially in semi-enclosed regions. These insights reinforce the relevance of water age as a diagnostic tool for understanding estuarine functioning and contribute to the broader discourse on water as a transformative agent in shaping ecological processes, sediment transport, and human–environment interactions in tropical coastal zones.

Despite the robustness of the modeling framework, it is important to recognize certain limitations that may affect the precision of the results. Constraints include the spatial resolution of input datasets, the simplifications applied to physical processes such as sediment–water interactions, and the assumptions inherent in the passive tracer method used to estimate water age. Additionally, the reliability of water inflow and tidal forcing data, although based on authoritative sources, may introduce localized uncertainties in the computed age fields. Nevertheless, the model successfully captures the dominant hydrodynamic patterns and offers a solid foundation for future investigations aimed at improving estuarine management and resilience in the Amazon region.

CONCLUSION

This study demonstrates that water age in the Amazon and Pará Rivers is strongly modulated by seasonal variations in river discharge. Shorter residence times prevail during the high-water period, whereas significantly longer renewal times are observed during low-flow conditions, especially in semi-enclosed regions such as Bocas Bay. These patterns influence the estuarine flushing capacity and have direct implications for water quality, sediment transport, and biogeochemical processes, particularly under prolonged low-discharge scenarios.

The modeling framework employed proved to be a robust tool for simulating spatial and temporal variability in water age, offering valuable insights into how hydrodynamic processes regulate ecosystem dynamics in large-scale estuarine systems. By contributing to a better understanding of estuarine functioning in a tropical context, this work supports integrated water resource management strategies. Future research should focus on refining sediment–water interactions and exploring scenarios of climate change and anthropogenic pressures to enhance the predictive capacity of water age modeling in dynamic and vulnerable coastal environments such as the Amazon estuary.

ACKNOWLEDGEMENTS

This study was supported by the Secretariat of Science, Technology and Higher, Professional and Technological Education of the State of Pará – SECTET (Agreement PDI 002/2021). Author M.L.C. Barros acknowledges financial support from SECTET and from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA/INPA). The authors also thank the SisBaHiA Laboratory (COPPE/UFRJ), especially Patrícia Rosman, for the technical assistance provided for the proper use of the SisBaHiA modeling system.

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