

Modelling nutrient dynamics in a large tropical semiarid river-reservoir system

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Research Article

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Modelling nutrient dynamics in a large tropical semiarid river-reservoir system

Abstract: A simple process-based model was developed to predict total inorganic nitrogen (TIN) concentrations in the largest semiarid river-reservoir system in Brazil, building on a previously developed model for total phosphorus (TP). The model solved the monthly water balance and TIN dynamics along the river, assuming complete mixing within each cross-section, steady-state conditions, piston-flow transport, and first-order decay. Wastewater, reservoir, and river flow rates, together with TIN concentration data, were used for model validation. A consistent decrease in TIN concentrations was observed along the river, with a decay coefficient of 0.3 day^{-1} , identical to that previously reported for TP. Model calibration resulted in satisfactory performance, with an R^2 of 0.74 and a PBIAS of 20%. While TIN concentrations from point sources (PS) were assumed to be constant, a watershed runoff TIN concentration of 2.0 mg/L was calibrated for non-point sources (NPS), approximately five times higher than the corresponding value previously reported for TP due to greater mobility of nitrogen. On the other hand, this runoff TIN concentration was lower than those reported in humid regions, which may be attributed to the lower precipitation levels, intermittent river regime, and high-density reservoir network characteristic of the Brazilian semiarid region. NPS accounted for 23-99% of the total TIN load. A logarithmic function was proposed to relate the relative contribution of NPS as a function of river discharge, and it also described well TP data. Simulations for both nitrogen and phosphorus were performed to assess the effects of river discharge and remediation measures on water quality. The results indicated that the most critical conditions occur under high-flow regimes, when load reductions of approximately 50% for TN and 80% for TP are required to comply with the regulatory limits. The proposed model was also coupled with a reservoir nutrient model, yielding an increase in the TN:TP ratio with increasing discharge in both the river and reservoir due to the greater mobility of nitrogen, with the TN:TP ratio approaching approximately 10 at high discharges. Moreover, increasing reservoir volume reduced both TN and TP concentrations, but TP compliance remained much more limited than TN, highlighting the need for stricter phosphorus load-control measures. Because the proposed modelling framework relies on readily available hydrological and water quality data, it can also be applied to watersheds with different hydroclimatic conditions and land-use characteristics.

Keywords: hydroclimatic conditions; land use; modelling; non-point source; point source; nitrogen load.

1. Introduction

Total inorganic nitrogen (TIN), comprising ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-), represents the bioavailable fraction of nitrogen that directly drives eutrophication in inland waters, particularly in aquatic ecosystems where nitrogen is the limiting nutrient (Wiegand et al., 2020; Suresh et al., 2023; Varis and Zhao, 2026). A better understanding of TIN sources and transport pathways across watersheds is fundamental for quantifying nitrogen inputs to rivers, lakes and reservoirs and for designing effective water-quality management and restoration measures. Despite their importance, the interactions among hydrological processes, catchment characteristics, TIN loading and in-stream nitrogen dynamics remain poorly understood, particularly in tropical semiarid regions such as the Brazilian Northeast. In these regions, limited monitoring data, intermittent river systems and dense reservoir networks pose additional challenges for watershed modelling and require adaptations of existing approaches to adequately represent nitrogen transport processes at large spatial scales (Freire et al., 2023; Rocha and Lima Neto, 2023).

While TIN point sources (PS) mainly originate from municipal wastewater discharges, non-point sources (NPS) are primarily associated with surface runoff from agricultural land, livestock production and diffuse soil exports (Chapra, 2008; Lang and Yan, 2013; Mockler et al., 2017; Zhang et al., 2022; Li et al., 2024). These two nitrogen sources exhibit distinct production and transport mechanisms within watersheds. PS inputs tend to remain approximately constant throughout the year and are largely independent of river discharge, whereas NPS inputs are strongly flow-dependent and occur predominantly during rainfall-runoff events (Ding et al., 2010; Bowes et al., 2014; Wang et al., 2023; Xiao et al., 2024; Kaltenecker et al., 2025). Consequently, watershed-scale approaches that explicitly account for both PS and NPS are required to accurately quantify nitrogen delivery to rivers, reservoirs and lakes and to evaluate remediation strategies under different hydrological conditions. This challenge is even more pronounced in tropical semiarid watersheds, where precipitation is substantially lower than in humid regions, rivers are intermittent and may remain dry for at least half of the year, and reservoir networks are highly dense, with up to approximately seven small reservoirs per km^2 (Rabelo et al., 2021, 2022; Toné et al., 2023).

Empirical, process-based and machine-learning models have been applied to predict nutrient concentration and loads in tropical semiarid watersheds. Empirical models using emission factors remain the most widely adopted approach for estimating watershed nutrient loads in these regions, but they only provide average estimates of nitrogen contributions from PS and NPS without accounting for hydrological variability (Lacerda et al., 2018; Paula Filho et al., 2019). More recently, Lima Neto (2025) developed a parsimonious process-based model

considering complete mixing within each river cross-section, steady-state conditions, piston-flow transport and first-order decay. Although the model successfully described total phosphorus (TP) dynamics, its applicability to riverine nitrogen dynamics has not yet been investigated. Machine-learning approaches constitute an alternative for predicting nitrogen transport. However, they generally require the calibration of numerous parameters and extensive monitoring datasets to achieve satisfactory predictive performance. Moreover, to the best of our knowledge, the only machine-learning study focusing on nitrogen in tropical semiarid systems is that of Lima Neto (2026), which was restricted to reservoir environments.

The main objective of this study is to develop a parsimonious process-based model for predicting TIN dynamics in tropical semiarid basins by extending the TP model previously proposed by Lima Neto (2025). Specifically, the study aims to: (i) represent TIN inputs from PS and NPS together with in-stream first-order decay; (ii) apply the proposed model to the largest semiarid river in Brazil; (iii) quantify TIN loads from PS and NPS and evaluate their relative contributions under contrasting hydrological conditions; (iv) assess the reductions in nutrient loads required to comply with water-quality standards for different river discharge conditions; and (v) couple the proposed model with a reservoir model to investigate the impact of river discharge, reservoir volume and input load reduction on nutrient concentrations. By relying only on readily available hydrological and water-quality data while explicitly representing the dominant processes controlling nitrogen transport, the proposed model provides a practical alternative to more complex watershed models. Owing to its parsimonious formulation, it can also be applied to watersheds with different hydroclimatic conditions and land-use characteristics.

2. Material and methods

Figure 1 shows the study area, comprising the Salgado River Basin (SRB) and the Médio Jaguaribe River Basin (MJRB), which together form the main upstream drainage area of the Castanhão reservoir in the State of Ceará, in the Brazilian semiarid region. The basin is characterized by intermittent rivers, negligible baseflow and a dense reservoir network resulting from the crystalline geology, shallow soils and highly seasonal rainfall regime (Freire et al., 2023). Annual precipitation ranges from approximately 500 to 900 mm, whereas river discharge exhibits high seasonal variability, ranging from zero to about 750 m³/s, with an average inflow to the Castanhão reservoir of approximately 20 m³/s (Toné et al., 2023). The Castanhão Reservoir has a storage capacity of 6.7×10^9 m³ and is considered the largest water-supply

reservoir in Latin America, excluding dams primarily used for hydropower generation (Lima Neto, 2026).

The study focused on a 160-km river reach extending across the SRB and MJRB, including five monitoring cross-sections and the hydraulic connections to the Lima Campos, Orós and Castanhão reservoirs. River discharge and TIN concentrations were monitored by the Ceará State Environmental Agency (SEMACE) at the locations shown in Figure 1. Average flow rates and TIN concentrations from the Lima Campos and Orós reservoirs, as well as from wastewater treatment plants (WWTPs) in the municipalities of Aurora, Lavras da Mangabeira, Icó and Jaguaribe, were incorporated into the model as point sources. These data were obtained from the Water Resources Management Company of Ceará (COGERH) and the Water and Sewage Company of Ceará (CAGECE), respectively. A detailed description of the WWTPs, reservoirs and river network is available in Lima Neto (2025). Non-point-source TIN inputs generated by watershed runoff were estimated through model calibration.

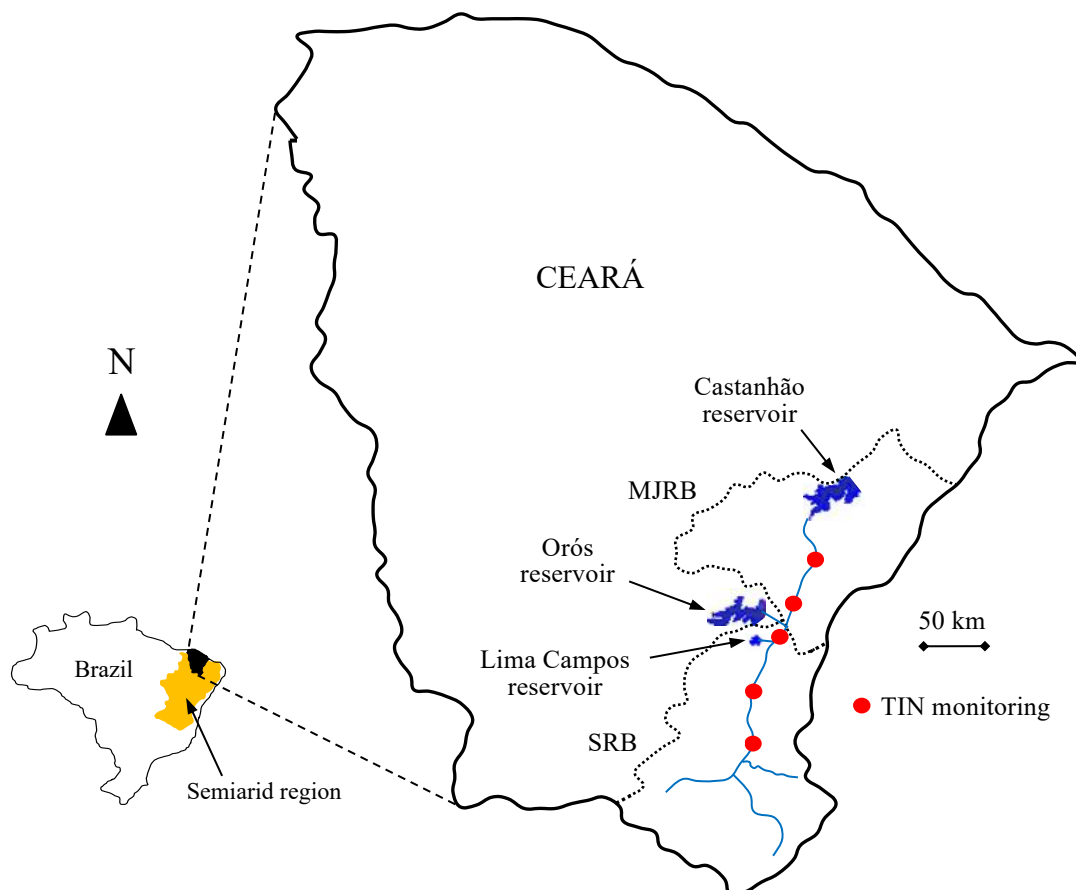


Figure 1. River stretch considered in the present study, including five cross-sections distributed along the Salgado River Basin (SRB) and Médio Jaguaribe River Basin (MJRB), together with the connections with the Lima Campos, Orós and Castanhão reservoirs.

The model developed in the present study was based on the model of Lima Neto (2025), which solves the monthly water balance and TP dynamics along the river, assuming complete mixing within each cross-section, steady-state conditions, piston-flow transport, and first-order decay.

The water balance along the river segments was solved numerically considering steady-state regime over a monthly time-step, according to Equation (1):

$$Q_{x+1} = Q_x + q_d \cdot \Delta x + Q_{p,i} \quad (1)$$

in which Q_x is the flow rate (m^3/s), x is the distance along the river segments, q_d is the non-point source (NPS) inflow to the river segment (m^2/s), Δx is the segment distance, assumed 1 km, and $Q_{p,i}$ is the point source (PS) inflow to the river segment (m^3/s), where i refers to each point source to the river system: Lima Campos and Orós reservoirs, and the municipalities of Aurora, Lavras da Mangabeira, Icó and Jaguaribe. The NPS inflow to the river system was assumed linearly distributed along the stretches, as given by Equation (2):

$$q_d = \frac{Q_{total} - \sum Q_{p,i}}{L_{total}} \quad (2)$$

in which Q_{total} is the monthly-averaged flow rate measured at the most downstream cross-section in the Médio Jaguaribe River Basin (MJRB), at the entrance of Castanhão reservoir, and L_{total} is the total length of the river system (see Figure 1).

The discharges along the river system were estimated by using Equations (1) and (2), as described in Lima Neto (2025).

The total inorganic nitrogen (TIN) balance was solved numerically assuming complete mixing at the cross-section, steady-state regime and a piston-type transport model with first-order decay:

$$TIN_{x+1} = \frac{Q_x \cdot TIN_x + q_d \cdot \Delta x \cdot TIN_d + Q_{p,i} \cdot TIN_{p,i}}{Q_{x+1}} - k \cdot TIN_x \cdot \left(\frac{\Delta x}{u_x} \right) \quad (3)$$

in which TIN_x , TIN_d and TIN_p are respectively the TIN concentrations (mg/L) in the segment, non point-sources (NPS) and point-sources (PS), k is the TIN decay coefficient (day^{-1}) and u_x

is the river flow velocity (km/day) at each segment, estimated as described by Lima Neto (2025).

The TIN decay coefficient was assumed $k = 0.3 \text{ day}^{-1}$, which is the same calibrated for TP in the SRB and MJRB (Lima Neto, 2025). In this sense, the only parameter to be adjusted in the model was the lateral inflow (runoff) concentration TIN_d . Hence, the complexities regarding the production and transport of non-point sources of TIN at the basin scale, also including the potential effect of small reservoirs disconnected to the main river system, are assumed to be incorporated in the fitting of TIN_d . Therefore, Equation (3) was solved by fitting the values of TIN_d that maximized R^2 and minimized the PBIAS between modelled and measured values of TIN at the five cross-sections in the MJRB. The calibrated values of TIN_d were analyzed and compared with previous studies.

A sensitivity analysis was performed to evaluate the influence of varying TIN concentrations at WWTP outlets (TIN_p) provided by CAGECE, which ranged from approximately 3 to 15 mg/L, with an average value of 8 mg/L.

The contribution of NPS to total TIN loads was investigated as a function of river discharge. An empirical relationship was developed for TIN and subsequently evaluated using TP data from Lima Neto (2025).

Model simulations were performed for the entire river network within the SRB and MJRB, covering approximately 300 km, to evaluate compliance with the regulatory limits for TN (2.18 mg/L) and TP (0.10 mg/L) established by CONAMA (2005) under different river discharge and load-reduction scenarios. TN concentrations were estimated by multiplying the simulated TIN concentrations by a factor of 2, consistent with the average TN-to-TIN ratio measured by CAGECE, COGERH and SEMACE. This enabled the assessment of the effects of river discharge on TP and TN concentrations and the TN:TP ratio in the river.

Finally, the proposed model was coupled with Equations (4) and (5), adapted from Lima Neto et al. (2022) and Rocha and Lima Neto (2021, 2023), to assess the impact of river discharge, reservoir volume and input load reduction on the water balance, TP and TN concentrations, as well as the TN:TP ratio in the Castanhão reservoir (see Figure 1).

$$dV/dt = Q_{in} - Q_{out} \quad (4)$$

$$d(V \cdot C)/dt = Q_{in} \cdot C_{in} + W_f - k \cdot V \cdot C - Q_{out} \cdot C \quad (5)$$

in which V is the reservoir volume, Q_{in} and Q_{out} are the reservoir inflow (including river discharge) and outflow (including evaporation, spillage and withdrawal), respectively, C is the nutrient (TP or TN) concentration in the reservoir, C_{in} is the inflow nutrient concentration, W_f is the fish farming load, and k is a global decay rate for each nutrient, which are given by Lima Neto (2026).

3. Results and discussion

Figure 2 shows that the proposed model reproduced well the longitudinal variation of TIN concentrations across the five monitoring cross-sections in the Salgado River Basin (SRB) and the Médio Jaguaribe River Basin (MJRB) (see Figure 1), considering the average TIN concentration at WWTP outlets of $TIN_p = 8 \text{ mg/L}$ and the first-order decay coefficient of $k = 0.3 \text{ day}^{-1}$, and adjusting the runoff concentration to $TIN_d = 2 \text{ mg/L}$.

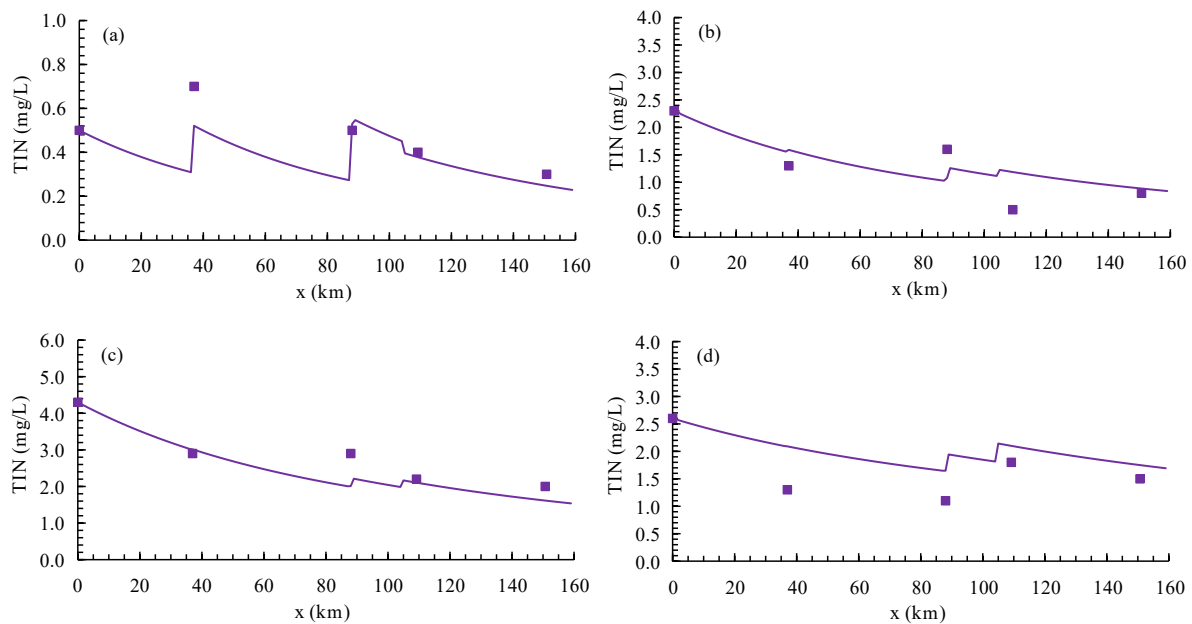


Figure 2. Model predictions of the longitudinal variation of total inorganic nitrogen (TIN) concentrations across the five monitoring cross-sections in the SRB and MJRB for different river discharges: (a) $Q = 2.1 \text{ m}^3/\text{s}$ (06/2018), (b) $Q = 6.3 \text{ m}^3/\text{s}$ (02/2019); (c) $Q = 15.2 \text{ m}^3/\text{s}$ (05/2021); and (d) $Q = 46.5 \text{ m}^3/\text{s}$ (03/2018).

Table 1 summarizes the model performance metrics for each river discharge (Q). The PBIAS values ranged from -10% to 28%, whereas R^2 varied between 0.61 and 0.87 across the evaluated flow conditions. In general, the model achieved mean values of PBIAS of $\pm 20\%$ and R^2 of 0.74, corresponding to “good” and “very good” performances, respectively, according to the criteria proposed by Moriasi et al. (2015). The first-order decay coefficient adopted for TIN

($k = 0.3 \text{ day}^{-1}$) was the same as that previously calibrated by Lima Neto (2025) for TP in the same river reach, indicating that satisfactory simulations could be achieved without modifying the in-stream nutrient removal rate. This value is also consistent with that calibrated for TP in other rivers in the State of Ceará (Lima et al., 2018) and falls within the typical range of 0.2-0.4 day^{-1} reported for Brazilian rivers (Von Sperling, 2007). Similar values of k have also been reported by Chapra (2008) for rivers in temperate regions. In contrast, the calibrated runoff concentration ($\text{TIN}_d = 2.0 \text{ mg/L}$) was approximately five times higher than the corresponding TP concentration reported by Lima Neto (2025). This difference is physically consistent with the greater mobility of nitrogen compared with phosphorus, as nitrogen is predominantly transported in dissolved forms, whereas phosphorus is more strongly associated with the particulate phase during runoff events (Wang et al., 2023; Xiao et al., 2024). Consequently, diffuse runoff in the Castanhão reservoir watershed is expected to export greater nitrogen than phosphorus loads (Paula Filho et al., 2019). However, the value of $\text{TIN}_d = 2.0 \text{ mg/L}$ is below the minimum concentrations obtained by Lang and Yan (2013) and Li et al. (2024) for humid regions. The relatively low TIN_d value compared with those reported in the previous studies is attributed to lower precipitation levels, intermittent river regimes, and high-density reservoir networks, which are characteristic features of the Brazilian semiarid region. Table 1 also presents a sensitivity analysis of model performance for different TIN concentrations at WWTP outlets. Even for the extreme values of $\text{TIN}_p = 3$ and 20 mg/L , the resulting PBIAS and R^2 values remained within the satisfactory performance range according to Moriasi et al. (2015). As expected, the influence of WWTP effluent concentrations decreased with increasing river discharge, as non-point sources became proportionally more important. Overall, these results support both the robustness of the adopted decay coefficient (k) and the plausibility of the calibrated runoff TIN concentration (TIN_d).

Table 1. Model performance for each river discharge (Q), including the main results for $TIN_p = 8$ mg/L and a sensitivity analysis for the extreme values of $TIN_p = 3$ and 15 mg/L.

Q (m ³ /s)	Metrics	TIN_p (mg/L)		
		8	3	15
2.1	PBIAS	-9%	-27%	28%
	R ²	0.70	0.35	0.44
6.3	PBIAS	28%	24%	26%
	R ²	0.61	0.59	0.63
15.2	PBIAS	-10%	-11%	-9%
	R ²	0.87	0.87	0.87
46.5	PBIAS	24%	23%	24%
	R ²	0.80	0.80	0.80

Figure 3 shows the relative contribution of non-point sources (NPS) to the total nutrient load (PS + NPS) as a function of river discharge. The relationship was accurately described by the following empirical function:

$$NPS/(PS + NPS) = 1 - \exp(-0.3Q^{0.7}) \quad (6)$$

The curve fitting yielded PBIAS = 14% and $R^2 = 0.90$, which indicates very good model performance according to the criteria of Moriasi et al. (2015). Similar performance was obtained for TP based on the dataset reported by Lima Neto (2025), with PBIAS = 5% and $R^2 = 0.86$. These consistent results suggest that the same functional relationship can be used to represent the relative contribution of NPS for both nitrogen and phosphorus loads in the studied river system. The contribution of NPS increased rapidly with increasing discharge, from approximately 25% under very low-flow conditions to more than 90% for river discharges above approximately 15-20 m³/s. At higher discharges, the relationship asymptotically approached unity, indicating that diffuse sources became the predominant contributors to total nutrient loads. Conversely, point sources were mainly relevant during low-flow periods, when limited dilution and reduced surface runoff enhanced their relative contribution. These findings highlight the strong dependence of nutrient source dynamics on hydrological conditions, with NPS dominating during moderate and high-flow events and PS controlling nutrient inputs during baseflow conditions, consistent with the results of Bowes et al. (2008, 2014), Rattan et al. (2021) and Rocha et al. (2021).

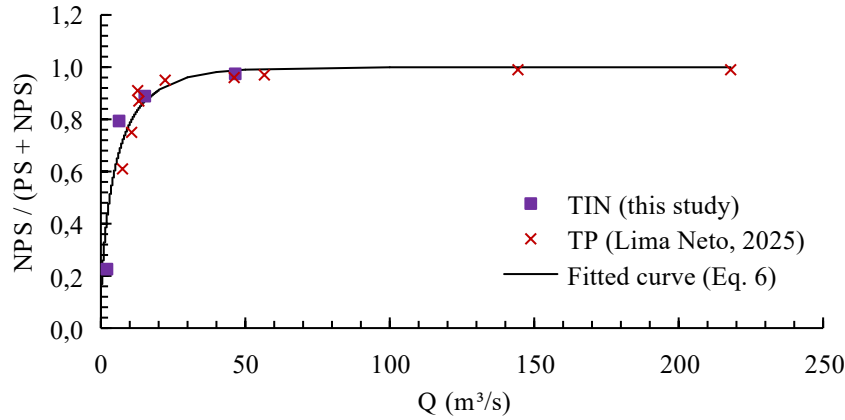


Figure 3. Relative contribution of non-point sources (NPS) to the total nutrient load (PS + NPS) as a function of river discharge (Q).

Figures 4 and 5 present model simulations for the entire river network within the SRB and MJRB to evaluate compliance with the regulatory limits for TN (2.18 mg/L) and TP (0.10 mg/L) established by CONAMA (2005) under different river discharge and load-reduction scenarios. Total nitrogen concentrations were estimated by multiplying the simulated TIN concentrations by a factor of 2, consistent with the average TN-to-TIN ratio measured by CAGECE, COGERH, and SEMACE. Figure 4 shows the results for low-flow conditions ($Q = 2 \text{ m}^3/\text{s}$), under which TN complies with the regulatory limit throughout the river network, whereas TP requires a 60% load reduction to meet the standard. Under high-flow conditions ($Q = 750 \text{ m}^3/\text{s}$), shown in Figure 5, the required load reductions increase to 50% for TN and 80% for TP. The above simulations indicate that achieving compliance with the TP standard is considerably more challenging than with the TN standard, particularly under moderate and high-flow conditions, highlighting the need for more stringent phosphorus load-control measures, as already reported by Paula Filho et al. (2019).

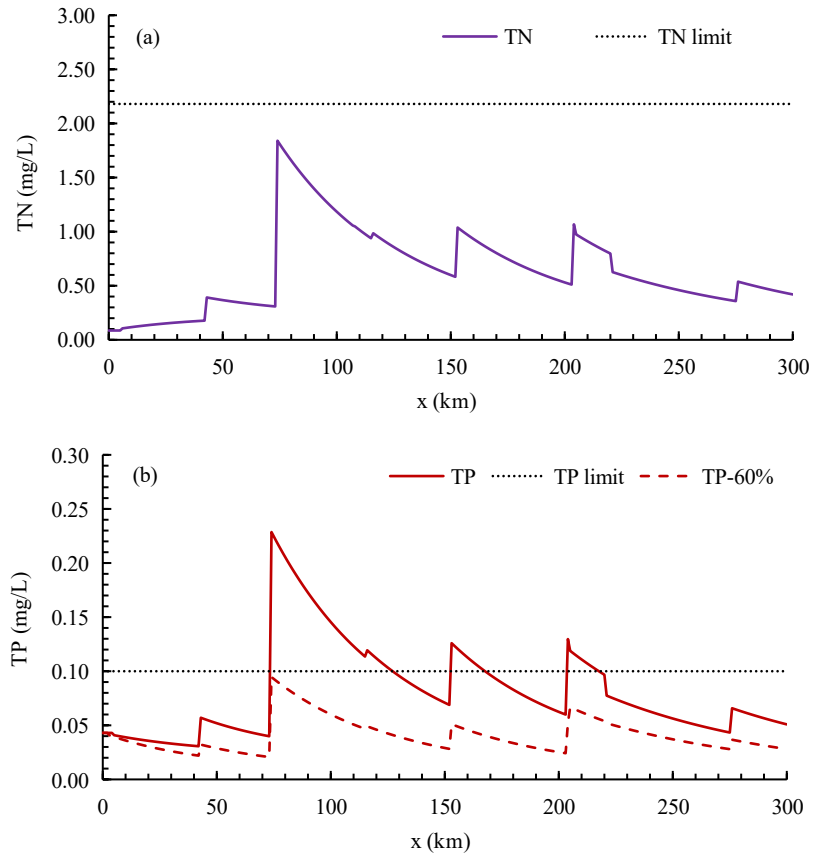


Figure 4. Model simulations within the SRB and MJRB showing the load reductions required to achieve compliance with the regulatory limits under low-flow conditions ($Q = 2 \text{ m}^3/\text{s}$): (a) no TN load reduction; (b) 60% TP load reduction.

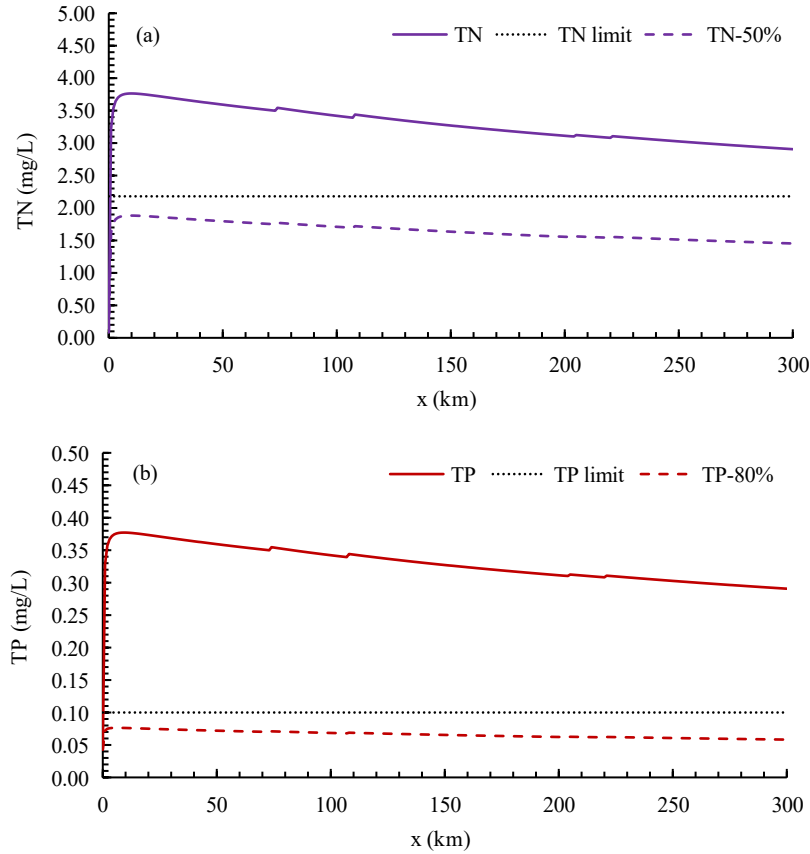


Figure 5. Model simulations within the SRB and MJRB showing the load reductions required to achieve compliance with the regulatory limits under high-flow conditions ($Q = 750 \text{ m}^3/\text{s}$): (a) 50% TN load reduction; (b) 80% TP load reduction.

Coupling the river and reservoir nutrient models enabled assessment of the effects of discharge on TN and TP concentrations and the TN:TP ratio in both the river and reservoir. A storage volume equivalent to 50% of the Castanhão reservoir's capacity was considered in the simulations. Figure 6 illustrates the variation in compliance with the regulatory limits established by CONAMA (2005). TN concentrations exceeded the limits of 2.18 and 1.27 mg/L in the river and reservoir, respectively, at discharges higher than 100 and 535 m^3/s . For TP, the regulatory limit of 0.10 mg/L in the river was exceeded at discharges above 8 m^3/s , whereas the regulatory limit of 0.03 mg/L in the reservoir was exceeded even at zero discharge. The results also indicated an increase in the TN:TP ratio with increasing discharge in the river, attributed to the greater mobility of nitrogen in the Castanhão reservoir watershed, as reported by Paula Filho et al. (2019) and Lima Neto (2026). The TN:TP ratio approached approximately 10 at high discharges. This value falls within the range commonly associated with a transition between phosphorus and nitrogen limitation in tropical semiarid reservoirs, although TN:TP

ratios can vary substantially among rivers and reservoirs depending on nutrient sources, river discharge and reservoir volume (Wiegand et al., 2020).

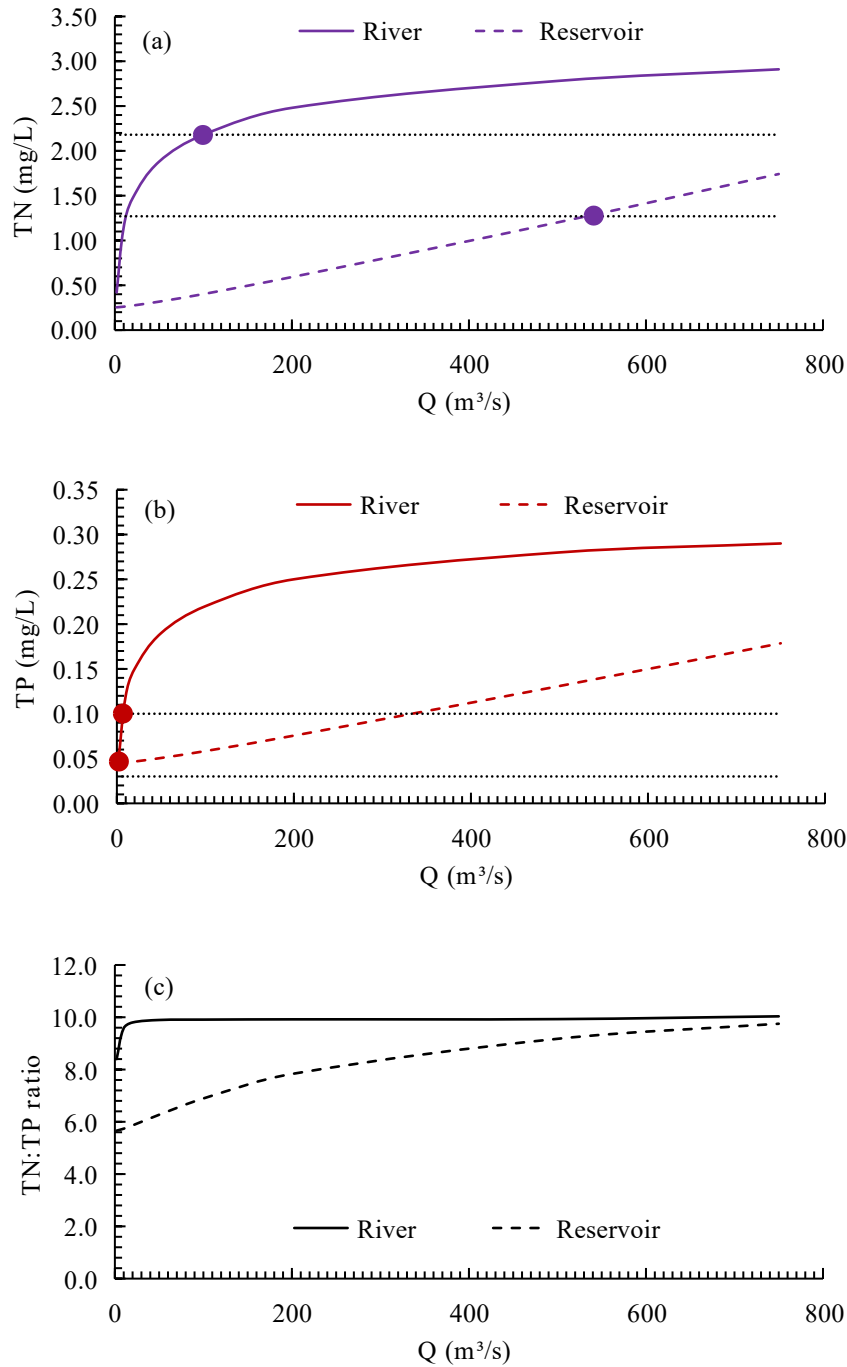


Figure 6. Simulation of TN (a), TP (b), and the TN:TP ratio (c) in the river and reservoir, with circles indicating the river discharge (Q) above which the regulatory limits are exceeded.

Finally, Figure 7 shows the impact of reservoir volume on compliance with the regulatory limits established by CONAMA (2005), considering a typical inflow of $Q = 20 \text{ m}^3/\text{s}$ during the wet season (January-June), zero inflow during the dry season (July-December), and

a typical reservoir outflow of 10 m³/s. Increasing reservoir volume clearly reduces both TN and TP concentrations. While TN remained below the regulatory limit (<1.27 mg/L) for reservoir volumes ranging from 10% to 90%, TP complied with the standard (<0.03 mg/L) only during April-May, June-July and September-October for reservoir volumes of 90%, 50% and 30%, respectively. These results are consistent with the substantially lower compliance of TP compared with TN in tropical semiarid reservoirs (Rocha and Lima Neto, 2021, 2023; Lima Neto, 2026). Moreover, model simulations also showed that a 50% reduction in the TP input load at a reservoir volume of 30% (approximately the current volume of Castanhão reservoir) could shift the onset of compliance from September-October to July-August. These results confirm that achieving compliance with the TP standard is considerably more challenging than with the TN standard, particularly at lower reservoir volumes, thus requiring more stringent phosphorus load-control measures (Bowes et al., 2014; Lima Neto et al., 2022).

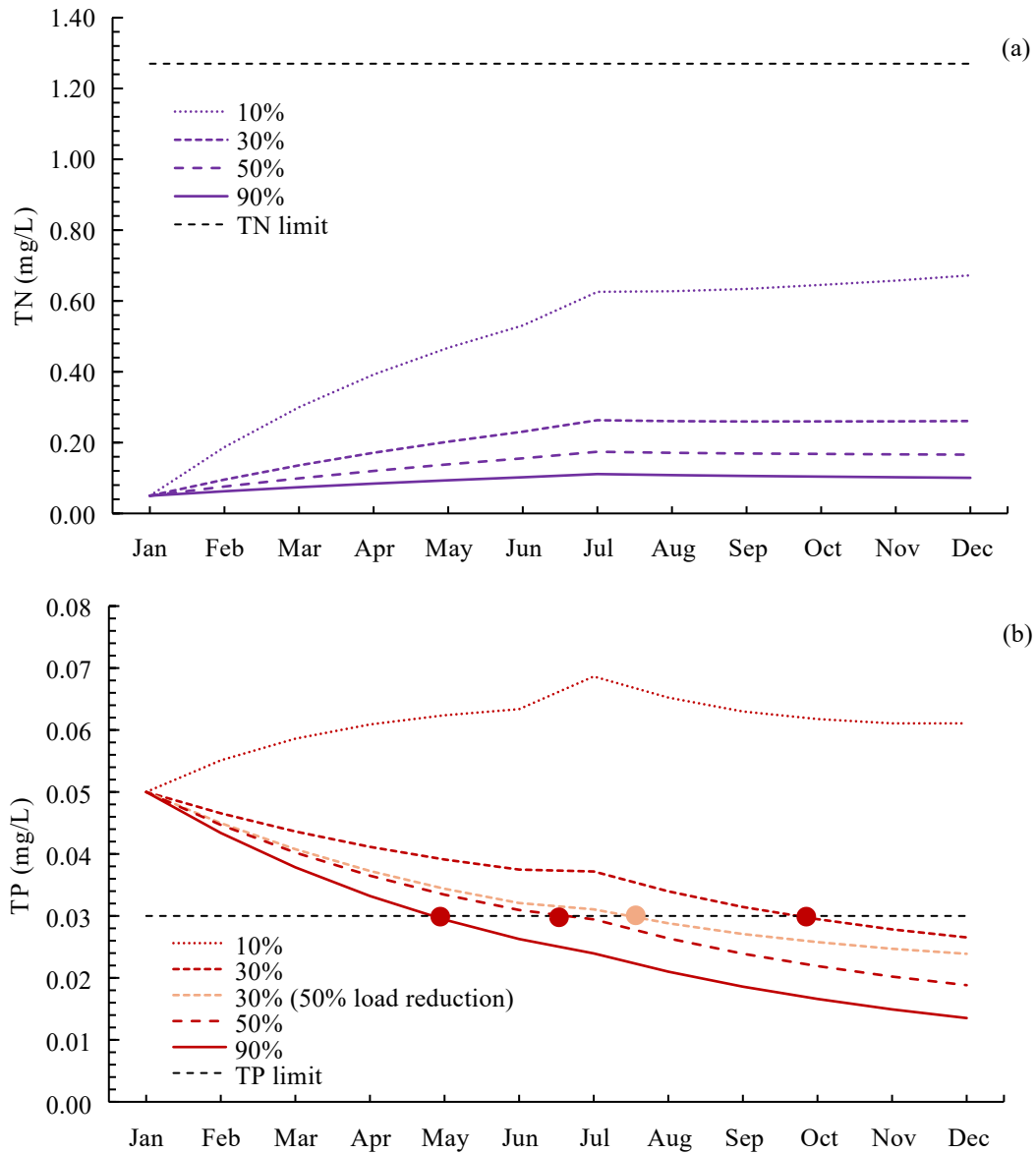


Figure 7. Simulation of the effects of reservoir volume (10-90%) and input load reduction (50%) on compliance with the regulatory limits for TN (a) and TP (b), with circles indicating the onset of compliance.

4. Conclusions

A simple process-based model was developed herein to predict TIN concentrations in the largest semiarid river in Brazil using hydrological and water quality data. Despite its conceptual simplicity, the model accurately reproduced the longitudinal distribution of TIN concentrations, achieving good performance ($R^2 = 0.74$ and $PBIAS = 20\%$). The calibrated first-order decay coefficient ($k = 0.3 \text{ day}^{-1}$) was identical to that previously obtained for TP, suggesting that a common decay rate may be applicable to both nutrients under the prevailing hydroclimatic conditions. The calibrated runoff TIN concentration (2.0 mg/L) was

approximately five times higher than the corresponding TP concentration, highlighting the greater mobility of nitrogen in diffuse watershed runoff. On the other hand, this runoff TIN concentration was lower than reported in previous studies in humid regions, which was attributed to the lower precipitation levels, intermittent river regime and high-density reservoir network, characteristic of the Brazilian semiarid region. Non-point sources dominated TIN inputs under most hydrological conditions, contributing between 23% and 99% of the total load. Furthermore, a simple empirical function was proposed to quantify the relative contribution of non-point sources as a function of river discharge, and its applicability to both nitrogen and phosphorus provides a practical approach for nutrient source apportionment. Scenario analyses indicated that water quality deterioration becomes more pronounced under high-flow conditions due to the increasing contribution of diffuse pollution. To comply with Brazilian water quality standards, reductions of approximately 50% in TIN loads and 80% in TP loads are required during high-flow events, indicating that phosphorus control remains the greatest challenge for watershed restoration. The river nutrient model was also coupled with a reservoir nutrient model, yielding an increase in the TN:TP ratio with increasing discharge in both the river and reservoir due to the greater mobility of nitrogen, with the ratio approaching approximately 10 at high discharges. The simulations also showed that increasing reservoir volume reduced both TN and TP concentrations. However, while TN remained compliant across all simulated volumes, TP compliance was substantially more limited and could be extended by reducing TP inputs, highlighting the need for stricter phosphorus load-control measures in tropical semiarid reservoirs. Since the proposed modelling approach relies only on commonly monitored hydrological and water quality variables, it provides a practical and transferable framework for assessing nutrient dynamics, identifying dominant pollution sources, and supporting the development of remediation strategies across semiarid and other river basins with contrasting hydroclimatic and land-use characteristics.

5. Declarations

- Ethics approval and consent to participate: Not applicable
- Consent for publication: Not applicable
- Availability of data and materials: Data available upon request
- Competing interests: The author declares that he has no competing interests

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