



Effects of rainfall and land use on nutrient responses in rivers in the Brazilian semiarid region

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Abstract This paper investigated whether rainfall promotes dilution or increase in nutrient concentrations and which land use indicators are the main predictors of nutrients in intermittent rivers in a large Brazilian semiarid region. The total phosphorus (TP) and total inorganic nitrogen (TIN) were monitored between 2013 and 2018 at 92 river water quality monitoring sites. The monthly rainfall (Rn) was obtained from 575 rain gauges. Pearson's correlation (R) between Rn and nutrient concentration was performed. The correlation patterns were also analysed based on land use data: urban area (%), agricultural field area (%), demographic density (inhabitants/km²), sewer system coverage (%), and reservoir density (reservoir/km²). Backward stepwise regression was performed to identify predictors of nutrient concentrations. The results revealed a marginal effect of rainfall on nutrients when the effects of urbanisation outweigh all other aspects. However, in regions with greater accumulated rainfall and lower reservoir density, the rainfall was related to a linear increase in nutrient concentrations ($R > 0.8$). Contrastingly, in

the basins with less accumulated rainfall and greater inter-basin hydrological disconnection, there was a linear reduction in nutrient concentration ($R < -0.5$). In the backward stepwise regression, sewer system coverage and Rn had the greatest influence for TP, and the urban area was the strongest predictor for TIN. Importantly, our results demonstrated that in semiarid rivers in densely populated regions, there is no single pattern of variability in nutrient concentration, on a wide scale of assessment. Therefore, adaptive and decentralised management can be more effective in improving water quality in these regions.

Keywords Phosphorus · Nitrogen · Water quality monitoring · Intermittent rivers · Sources of pollution · Pearson's correlation · Backward stepwise regression

Introduction

Surface run-off and land uses are the main sources of nitrogen and phosphorus exports to water resources (Rocha & Lima Neto, 2021; Wadnerkar et al., 2021). The influence of land use on water quality depends on regional conditions, whether anthropogenic (types of agricultural crops, irrigation system, urban organisation) or environmental (soil types, climate) (Lee et al., 2009; Liu et al., 2018). For this reason, an assessment of the variation of nutrient concentrations can differ significantly in spatial scale (Cruz

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et al., 2019; Li et al., 2022). Spatial non-stationarity in the relationship between nutrients and water quality has attracted the interest of many researchers and water resources managers to identify the “source” and “sink” of pollution activities (Chen et al., 2003; Jiang et al., 2013; Xu et al., 2019). It is known that replacing forests with agricultural areas and urban areas increases nutrient concentrations in watersheds (Namugize et al., 2018). This increase is related to bare soil and may be influenced by livestock density in adjacent areas (Julian et al., 2017). In this sense, agriculture, urbanisation, and mining are the main sources of water quality deterioration in Brazil (Mello et al., 2020).

On the other hand, hydrological processes and water quality are also directly influenced by atmospheric weather phenomena in the Southern Hemisphere (Li & McGregor, 2017). Between 2015 and 2016, there was a strong El-Niño comparable to those of 1982/1983 and 1997/1998 (Lim et al., 2017). This occurrence was related to the sequence of dry years between 2012 and 2017 in Northeast Brazil (Marengo et al., 2018). During this period, Wiegand et al. (2021) found that the trophic state index (TSI) for 53 reservoirs in Ceará, included in the Brazilian semi-arid region, reached hypertrophic conditions. Tropical semi-arid reservoirs are vulnerable to eutrophication due to increased phosphorus concentrations and under climate change scenarios (Raulino et al., 2021). Retention of nutrients by reservoirs is overtaken by high rates of sedimentation, which increase internal loads over time (Rocha & Lima Neto, 2022). Consequently, older reservoirs become a source instead of a sink of phosphorus (Lima Neto et al., 2022). In the rainy season of drier years, nutrient concentrations increase in rivers in this region (Freire et al., 2021). The seasonality of rainfall also has a great influence on the dynamics of nutrients in reservoirs (Rocha and Lima Neto et al., 2021; Xue et al., 2016). In the dry season, a strong influence of point source discharges is expected, because of the reduction in the flow of intermittent rivers and the demand for improvements in sewage treatment systems in this region (Freire et al., 2021). Knowledge of how the nitrogen and phosphorus concentrations change during the rainy season is necessary to understand the processes of transport of these nutrients to the reservoirs, which are the main source of water supply for multiple activities in the region (De Araújo et al., 2018). Moreover,

water allocation is performed after the rainy season, in other words, after the period of the highest inflow of water to the reservoirs (Souza Filho et al., 2008).

Several studies investigated the relationships among nutrients, precipitation, and land use. A search for the subjects “nutrients, rainfall, land use, land cover, river,” using the Boolean operator “and” in the Web of Science database revealed 105 publications to date (Mar, 2023), with the most recurrent subjects shown in Fig. 1a. When the search was refined by entering water resource management, 28 papers were found (Fig. 1b). It is noteworthy that the links among land use, impacts, rainfall, nutrients, and management resulted in several recent publications, which indicates the current scientific interest in the topic. Observe that geographic information systems (GIS) and indicators have also been integrated into the search. However, when the subject “semiarid” was added to the search list, no results were found, which suggests a lack of studies in this direction.

In the Brazilian semi-arid region, low rainfall and thousands of reservoirs favour lower phosphorus loads compared to the national average, except for urban basins with low sanitation coverage (Rocha & Lima Neto, 2021). Some issues also deserve attention in this region: nutrient availability and changes in river flow resulted in the growth of phytoplankton communities, restricting water uses (Santana et al., 2016); the decrease in rainfall in recent years has often been associated with eutrophication due to agriculture, urbanisation, and land-use changes (Soares et al., 2021); most rivers are intermittent and heavily impacted by high concentrations of phosphorus and nitrogen (Freire et al., 2021); the Brazilian semi-arid region is one of the most populous in the world (Malveira et al., 2012).

Intermittent and ephemeral streams associated with several reservoirs also modify the dynamics of water quality (Lima Neto et al., 2011; Marques et al., 2019; Nascimento Filho et al., 2019). This study provides new insights into identifying patterns between land use and water quality in semi-arid regions on a wide spatial scale. Analysing this dynamic in regions with diverse environmental and anthropogenic aspects can be even more challenging (Ji et al., 2021; Shiferaw et al., 2022). Another key fact to remember is that, historically, water-soluble inorganic nitrogen species (ammonium, nitrite, and nitrate) represent an environmental concern and are

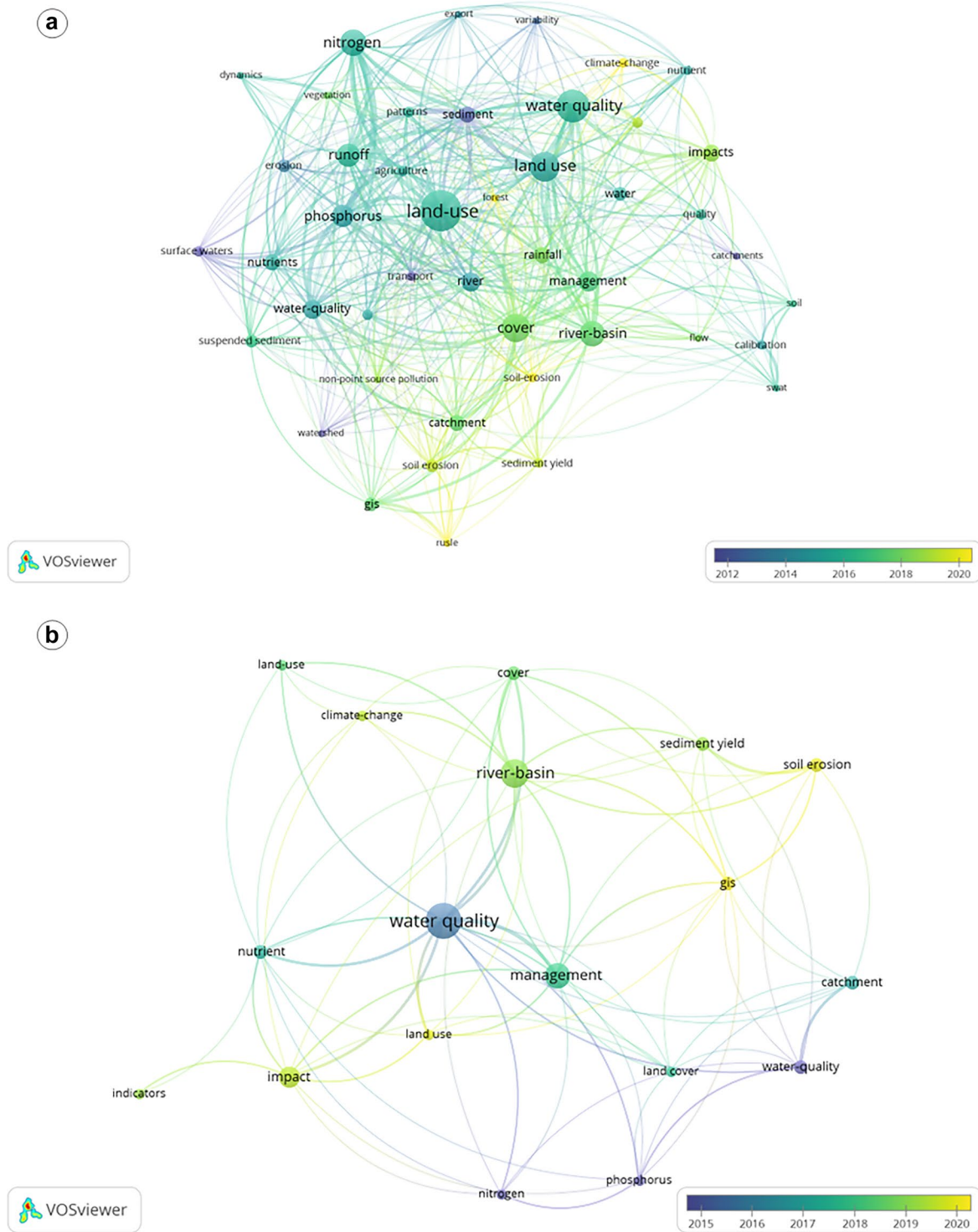


Fig. 1 Visualisation overlay network of keywords of Web of Science publications (**a** search by subjects: nutrients, rainfall, land use, land cover, river; **b** search by subjects: nutrients, rainfall, land use, land cover, river, water resource management)

part of the main water quality regulations (Sawyer et al., 2003). In this sense, globally, anthropogenic discharges considerably affect inorganic nitrogen concentrations in rivers (), and populated temperate zones and dry tropics and subtropics have the highest concentrations of phosphorus in the hydrological network (Savenko & Savenko, 2022). Therefore, the main objective of this paper was to evaluate the influence of rainfall and land use on total phosphorus (TP) and total inorganic nitrogen (TIN) concentrations in watersheds in the Brazilian semiarid region, on a spatial scale. The specific objectives were to assess whether rainfall influences the dilution or concentration of nutrients, and investigate

the relationship between land use indicators and nutrient concentrations in intermittent rivers.

Material and methods

Study area

The study area comprises eleven hydrographic regions in the State of Ceará (Fig. 2), mostly located in the Brazilian semiarid region, covering 142,384 km². The hydrographic regions of the State of Ceará are water resources planning units, which consider similar hydrological conditions, in addition to

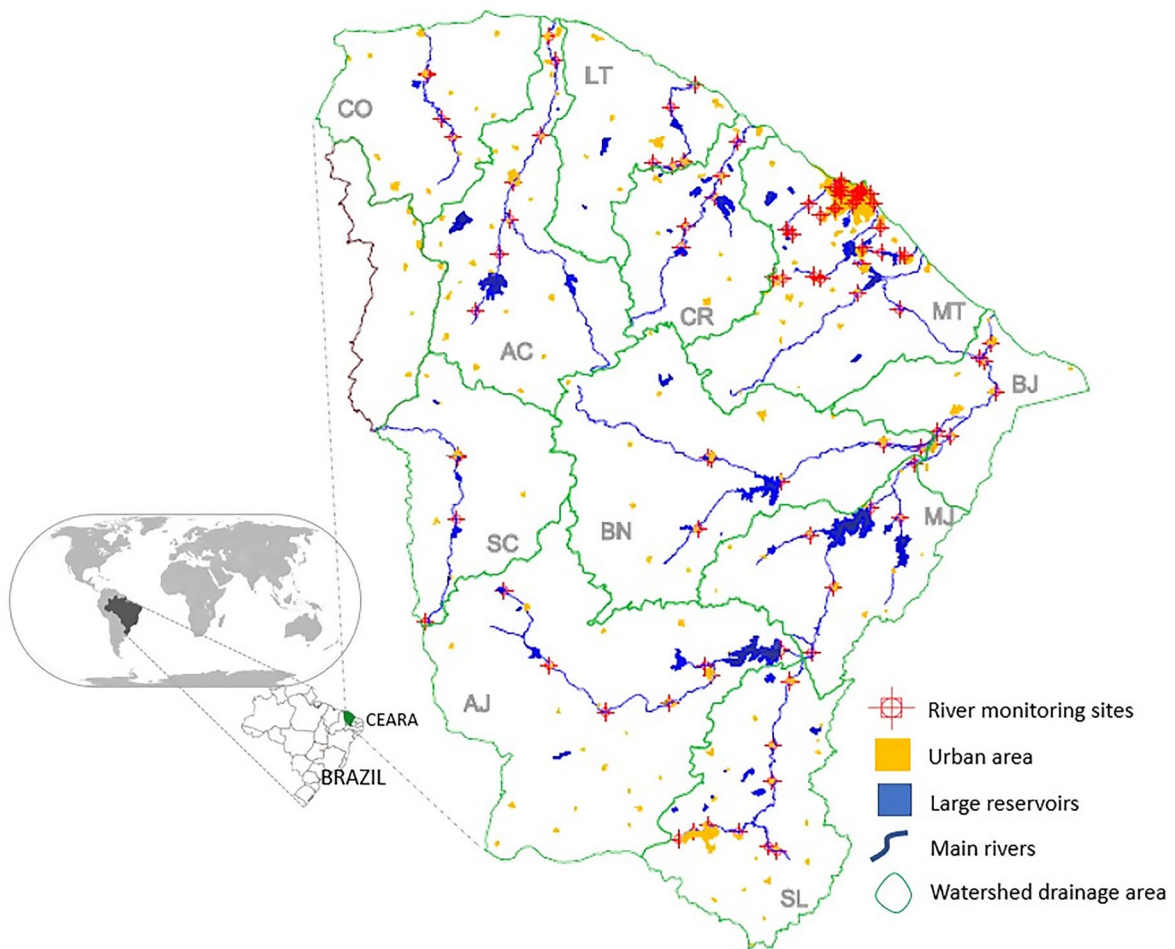


Fig. 2 Hydrographic regions, main river, urban area, and large reservoirs in study area (Acarauá (AC), Banabuiú (BN), Coreauá (CO), Curu (CR), Alto Jaguaribe (AJ), Médio Jaguaribe (MJ),

Baixo Jaguaribe (BJ), Litoral (LT), Metropolitanas (MT), Salgado (SL), and Sertões de Crateús (SC))

political-administrative issues. In this sense, eleven of the twelve hydrographic regions are included in the National Water Quality Monitoring Program and, therefore, were selected for the present research. They are named as follows: Acaraú (AC), Banabuiú (BN), Coreaú (CO), Curu (CR), Alto Jaguaribe (AJ), Médio Jaguaribe (MJ), Baixo Jaguaribe (BJ), Litoral (LT), Metropolitanas (MT), Salgado (SL), and Sertões de Crateús (SC). In these hydrographic regions, the average rainfall is about 550 to 1600 mm for driest (central and northwestern zones) and humid (coastal and plateau zones) zones of the territory, respectively (Uvo & Berndtsson, 1996). Watersheds in the vicinity of the coastal zone are influenced by instability lines due to the formation of rain clouds from solar incidence in the tropics (Gaiser et al., 2002). In the south of the State of Ceará, orographic rains are recurrent, influenced by the windward area of the SL watershed, where air masses from the coast reach the region and ascend through the relief (Costa et al., 2021). After the effects of the Intertropical Convergence Zone (ITCZ), the equatorial Atlantic mass starts to influence the formation of rain clouds from the formation of two air currents: one cool and wet and the other hot and dry (Uvo & Berndtsson, 1996). The rise of these currents, associated with thermal discontinuity and temperature reduction with altitude, generates heavy rains on the coast and drought in the interior and in the most central regions of the State of Ceará, where SC, BN, and AJ are located. The rainy season, in general, occurs between December and June, with more intense rains concentrated between February and May, which is favoured by the ITCZ. The other synoptic factors are easterly waves, cyclonic vortices, and climate change by El Niño-Southern Oscillation (ENSO). The El-Niño generates the displacement of the air mass ascendancy zone of the Walker cell and favours the occurrence of drier years in Northeastern Brazil, while the La-Niña is associated with the opposite condition in this region (Lim et al., 2017).

Data sources and statistical assessment

To assess whether precipitation influences the dilution or concentration of nutrients, two monitored variables were used: monthly rainfall and nutrient concentrations (TP and TIN). Ammonia, nitrite, and nitrate concentrations were considered as TIN. The monthly rainfall (R_n) for each hydrographic region

was provided by the Ceará Meteorology and Water Resources Foundation (Funceme). R_n was determined by the Thiessen Polygon Method (Thiessen, 1911) in 575 rain gauges in the study area. The Funceme is the agency responsible for monitoring meteorological conditions and water resources in the State of Ceará. Funceme provides precipitation data on the Ceará State Hydrological Portal (<http://www.hidro.ce.gov.br/>).

Nutrient concentrations, evaluated between 2013 and 2018, are part of a monitoring database of the National Water Quality Monitoring Program (<http://portalpnqa.ana.gov.br/>), and are related to the Resolution of the National Council for the Environment number 357/2005 (Brazil, 2005). In the national water quality monitoring network, the variables are selected and measured by state agencies for the environment, water resources, sanitation, and electricity sectors. In Ceará, the State Environment Agency (Semace) monitors rivers and provides water quality data. Sampling was carried out according to the National Guide for Collection and Preservation of Samples, established by the Resolution of the National Water Agency number 724/2011 (Brazil, 2011), and the variables were measured according to APHA (1998). In total, the data used came from 92 river water quality monitoring sites (Fig. 2).

First, simple linear regression and Pearson's correlation were performed with the log-transformed values of the average monthly nutrient concentrations and monthly rainfall, during the rainy season. Second, the linear relationship between the concentrations of TP and TIN was verified to understand the similarity of the dynamics of these nutrients.

Regarding the investigation of the influence of land use indicators on the nutrient concentrations, the predominant land uses in the study area were initially verified by accessing the MapBiomias platform (<https://mapbiomas.org/>). MapBiomias is an open access platform for geospatial land use and land cover data in Brazil based on automatic classification processes applied to satellite images (Souza et al., 2020). In the study region, 70.73% of the land cover corresponds to forests. The other land covers correspond to agriculture and livestock (24.03%), non-vegetated areas (2.25%), natural non-forest formation (2.25%), and water (0.94%). Also, according to the data obtained from MapBiomias, 24.95% of the territory of the State of Ceará has anthropogenic activities

and the main land use classes are agriculture and urbanisation. Therefore, the investigated anthropogenic interference indicators were those related to the predominant land uses: urban area (%), demographic density (inhabitants/km²), and sewer system coverage (%), which were related to the class of urban uses, while agricultural field area (%) was related to agricultural uses. Furthermore, provided that the dense network of reservoirs significantly alters the hydrology in this region (Rabelo et al., 2021, 2022), we considered reservoir density (reservoir/km²) as an indicator of anthropogenic changes.

In the study area, most crops are rainfed agriculture with conventional soil preparation (Medeiros et al., 2020). Subsistence and shifting agriculture are distributed along most watersheds, with some public and private irrigated fields (Studart et al., 2021; Martins et al., 2018). These forms of cultivation prevailed in the region between 1985 and 2018 (Sousa et al., 2021). Changes in organic matter and soil fertility in traditional shifting agriculture occur slowly and with great influence of vegetation, whose evaluation should consider the time of cultivation and bush fallow (Tiessen et al., 1992). However, it is clear that some watersheds have more agricultural or urban influence than others (Rocha & Lima Neto, 2021). Furthermore, spatial changes on water quality of rivers in this region are the most relevant (Freire et al., 2021). Therefore, the correlations between land use indicators and nutrients were carried out at the watershed scale.

The urban area was determined from vector files made available by the Research and Economic Strategy Institute of the State of Ceará (IPECE), using Quantum GIS 3.16. The municipal population data used to determine the demographic density and the sewer system coverage was made available by the National Sanitation Information System, whose average values were determined between 2013 and 2018. The agricultural fields area was made available by the Brazilian Institute of Statistical Geography (IBGE) for the year 2016. From these municipal data, the sum was carried out by hydrographic region. Then, the percentages were determined for the urban area, sewer system coverage, and agricultural fields area. Finally, the number of reservoirs to calculate the reservoir density was obtained from a map provided by Funceme, which defines the number of surface reservoirs per hydrographic region (Funceme, 2016).

Pearson's correlation and backward stepwise regression were performed between all analysed variables, including the average of Rn in the rainy season, the average concentration of TIN and TP, and the previously listed anthropogenic interference indicators. The backward stepwise method was used to infer the magnitude of the relationship between possible predictors of water quality (Lei et al., 2021; Wang et al., 2013; Wunderlin et al., 2001). The indicators of anthropogenic interference and the monthly rainfall were considered as independent variables, while nutrient concentrations were considered as dependent variables.

Results and discussion

Land use, rainfall, and nutrient concentration at the hydrographic region scale

The indicators of anthropogenic interference, the average nutrient concentration, and the average monthly rainfall were presented in Fig. 3. There is a similarity between the drainage area of the hydrographic regions, as most of them are within 10,000–20,000 km² (SL, SC, MT, MJ, CO, BN, and AC). On the other hand, three hydrographic regions (LT, CR, and BJ) cover between 5000 and 10,000 km², and one (AJ) covers more than 20,000 km². However, the metropolitan watersheds (MT) were the most urbanised, followed by SL. The least urbanised hydrographic regions were MJ and SC. In addition to the percentage of urban area, demographic density was also considerably higher in MT and SL, but lower in SC and BN. The percentage of agricultural fields area was higher in the AC watershed, followed by the LT and BJ, and was lower in MJ, BN and SL. Thus, MT and SL are hydrographic regions strongly influenced by urbanisation, while AC, LT, and BJ are more influenced by agricultural activities. However, in all hydrographic regions, agriculture is an important economic activity. In BJ and BN, for example, 70% of the available water is consumed by irrigated agriculture and, in these regions, the rapid agricultural expansion has caused conflicts in the use of water and intensified the risk of desertification and pollution (Lemos & Oliveira, 2004). Furthermore, according to Reis et al. (2020), the hydrographic region of the BJ is the one with the greatest



Fig. 3 Land-use indicators, nutrients concentration average, and monthly average rainfall per hydrographic region (Acarauá (AC), Banabuiú (BN), Coreau (CO), Curu (CR), Alto Jaguaribe (AJ), Médio Jaguaribe (MJ), Baixo Jaguaribe (BJ), Litoral (LT), Metropolitanas (MT), Salgado (SL) and Sertões de Crateús (SC))

vulnerability to drought, especially due to the high water demands for irrigation and shrimp farming.

Regarding the reservoir density (reservoir/km²), it is also necessary to observe (Fig. 4). The reservoirs in the region have different storage capacities. Most reservoirs have a maximum of 20 ha of lake surface area, as shown in Fig. 4. Northeastern Brazil has a linear relationship between the drainage area and the surface area of reservoirs (Freitas et al., 2011). The largest volumes stored are in the AJ, BN, and MJ. In AJ, for example, every 5 km² there would be one dam of water if these were evenly distributed. This number of reservoirs per area is the same as identified by Mamede et al. (2018) in a watershed in the State of Ceará.

The average concentrations of TP and TIN (Figs. 3 and 7) were higher in the more populated areas (MT and SL). In the case of SC that does not present high urbanisation rates, the values are directly influenced by the location of the monitoring rivers sites, as they are downstream of the stabilisation pond systems (Freire et al., 2021) similar to the influences of sewage treatment plants identified by He et al. (2023). These results corroborate those found by Lei et al. (2021), when identifying that the land use responses on water quality are more

perceived in the catchment scale, after comparing the catchment, riparian and reach scales. A more detailed approach to the relationship between the variables will be discussed below, with Pearson's correlation and the backward stepwise results.

Based on the results of the correlation between monthly rainfall and nutrient concentrations, it was possible to group the hydrographic regions, as shown in Fig. 5. The eccentricity of the ellipses is directly proportional to the magnitude of the correlation. This means that the greater the eccentricity, the closer is the correlation coefficient to the value of 1. Note that blue ellipses show positive correlations and red ellipses show negative correlations.

In hydrographic regions, TIN and TP are strongly correlated, except in AC, where the ratio between average TIN and TP was higher than in all other hydrographic regions. This may be related to higher phosphorus inputs, mainly from diffuse sources in agricultural fields along river banks. In this watershed, agriculture has been developed through irrigated perimeters in the vicinity of the main rivers (Cogerh, 2022), which may have contributed to the higher concentrations of TP in relation to TIN, because phosphorus may be more related to agricultural sources, while ammonia nitrogen with point

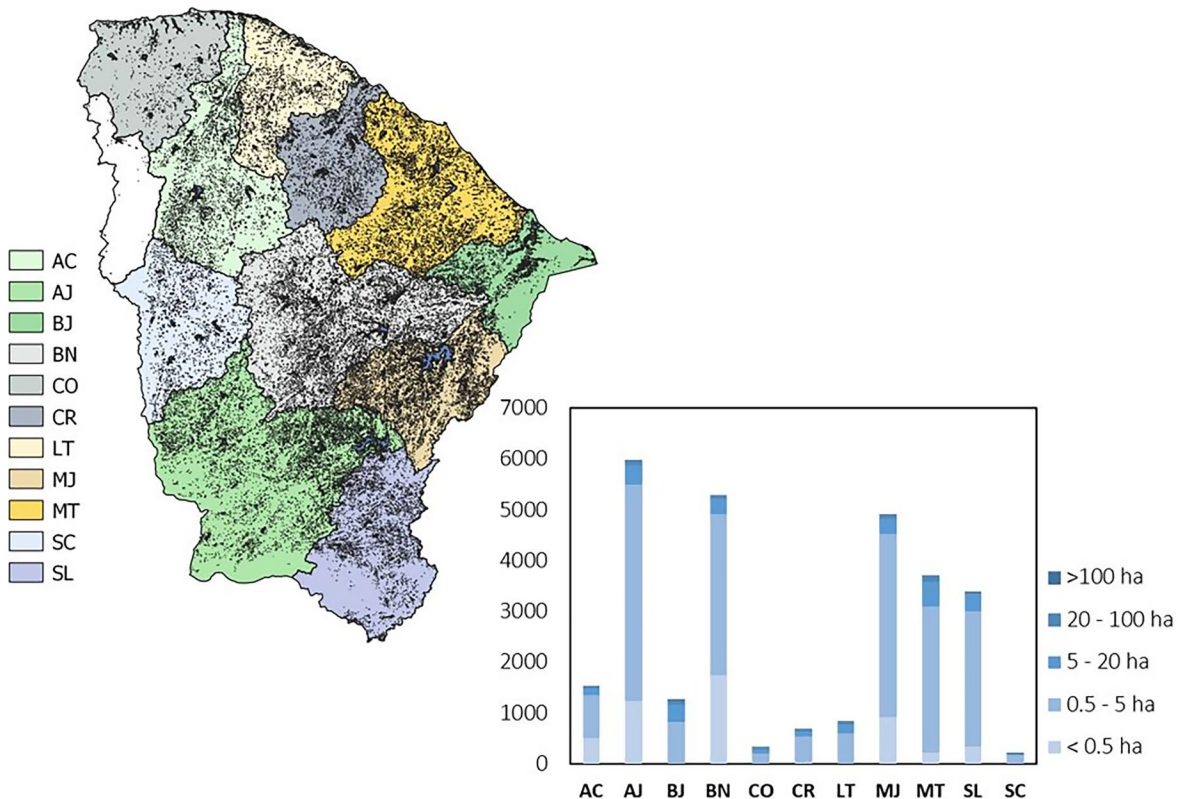


Fig. 4 Number of reservoirs per watershed per lake surface area (ha) (Acarauá (AC), Banabuiú (BN), Coreauá (CO), Curu (CR), Alto Jaguaribe (AJ), Médio Jaguaribe (MJ), Baixo Jag-

uaribe (BJ), Litoral (LT), Metropolitanas (MT), Salgado (SL) and Sertões de Crateús (SC))

pollution source of wastewater (Liberoff et al., 2018; Wang et al., 2015).

A positive relationship between rainfall and nutrients was identified for CO, CR, and AC, with CO being significant for both Rn versus TIN and Rn versus TP. On the other hand, a strong negative correlation coefficient for SL, SC, and AJ, with AJ being significant for the relationship between precipitation and both nutrient concentrations. The linear regression plots for these hydrographic regions are shown in Fig. 6.

The results revealed that different processes are related to nutrient response in rivers, where mechanisms mentioned by Uwimana et al. (2017) could be identified. A washout mechanism was verified in predominantly rural basins (CO, CR and AC), showing a positive relationship between nutrients and rainfall. Most positive correlations were more representative between Rn and TIN than between Rn and

TP, which corroborates Yao et al. (2021), who stated that soil nitrogen losses occur faster than phosphorus losses. Hence, increased precipitation more easily causes nitrogen leaching (Zhang et al., 2020). In CO, for example, where there is more intense rain and fewer reservoirs, the transfer of nutrients to the water sources is promoted on the same scale of correlation for TIN and TP, while in the others, where there is direct proportionality, the correlations are stronger for TIN.

The buildup and dilution mechanisms occurred in a correlated way — the dilution effect was stronger where there are more reservoirs, as in AJ watershed. The existence of several water dams (see Fig. 4) favours the trapping of nutrients by the reservoir network, through sedimentation and biological uptake, especially in years with below-average rainfall (Lima Neto et al., 2011; Molisani et al., 2012). Therefore, the inflow generated by rainfall reduced

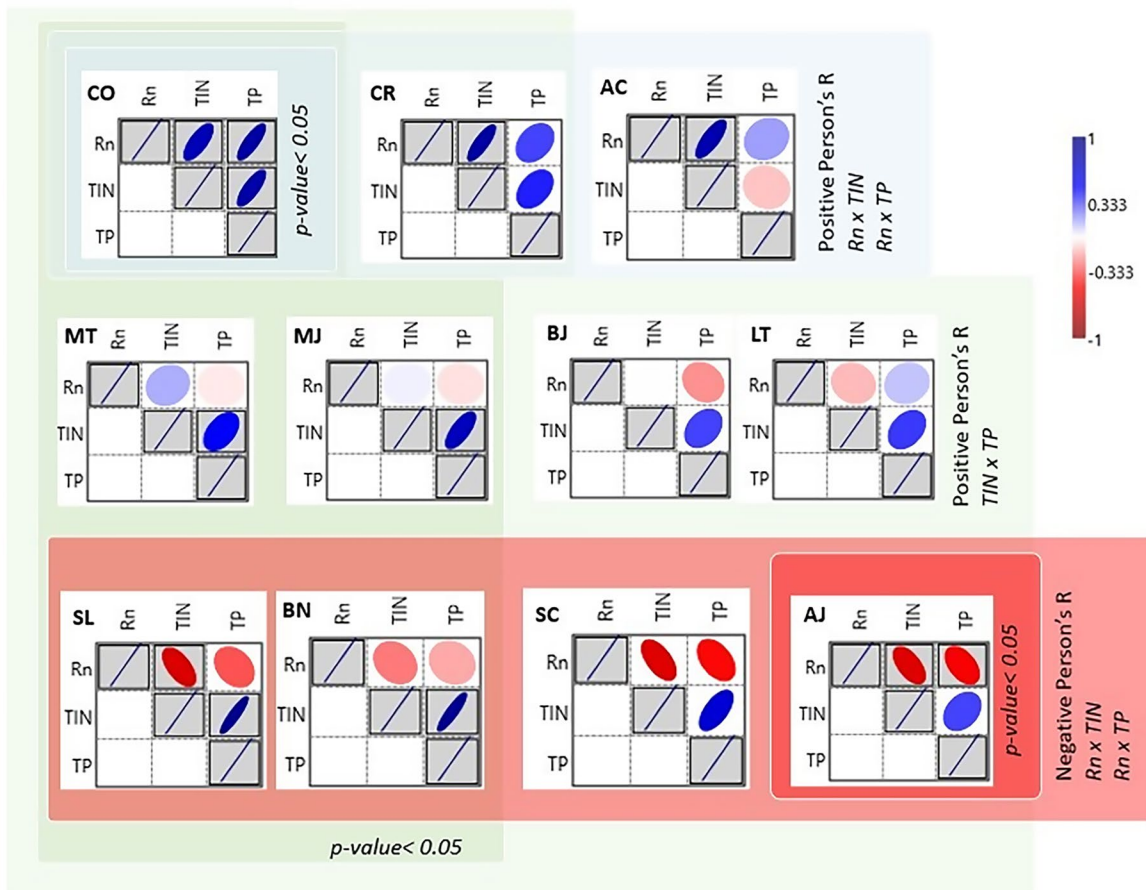


Fig. 5 Pearson's correlation (Rn×TIN, Rn×TP, TP×TIN) for each hydrographic region. (Rn, rainfall (mm); TIN, total inorganic nitrogen (mg/L); TP, total phosphorus (mg/L)). (Acarauá (AC), Banabuiú (BN), Coreaú (CO), Curu (CR), Alto Jaguar-

ibe (AJ), Médio Jaguaribe (MJ), Baixo Jaguaribe (BJ), Litoral (LT), Metropolitanas (MT), Salgado (SL), and Sertões de Crateús (SC))

the concentration of nutrients (inverse relationship between Rn and nutrients, see Fig. 6) in urban rivers, which are strongly impacted by point source pollution of wastewater. This occurrence is consistent with the one identified by Rocha and Lima Neto (2021) for 21 reservoirs located in the same region of the present study, where, in rural basins with thousands of small reservoirs, there was an input load of phosphorus of more than ten times lower than that of the national average. Consequently, the accumulation of these nutrients in the reservoirs increases their risk of eutrophication (Wiegand et al., 2021). Furthermore, high concentrations of cyanobacteria are already identified in the reservoirs of the evaluated sites, especially in drier zones (Lorenzi et al., 2018). In this

sense, the hydrological disconnection enhances this effect (Costa et al., 2012; Van Langen et al., 2021). On the other hand, for SC, the most influential factor is not the presence of reservoirs along with the hydrological network that promotes the positive relationship. In SC, the river water quality monitoring sites are downstream of waste stabilisation pond discharges. In this case, in the rainy season, surface runoff contributes to the dilution of this source of nutrient load. Dilution of pollutant loads during the rainy season is prevalent in places with point discharges of wastewater (Bowes et al., 2012; Freire et al., 2021).

In the most urbanised watershed (MT), the association between nutrients and Rn was not relevant, as well as in MJ and BJ. In these watersheds

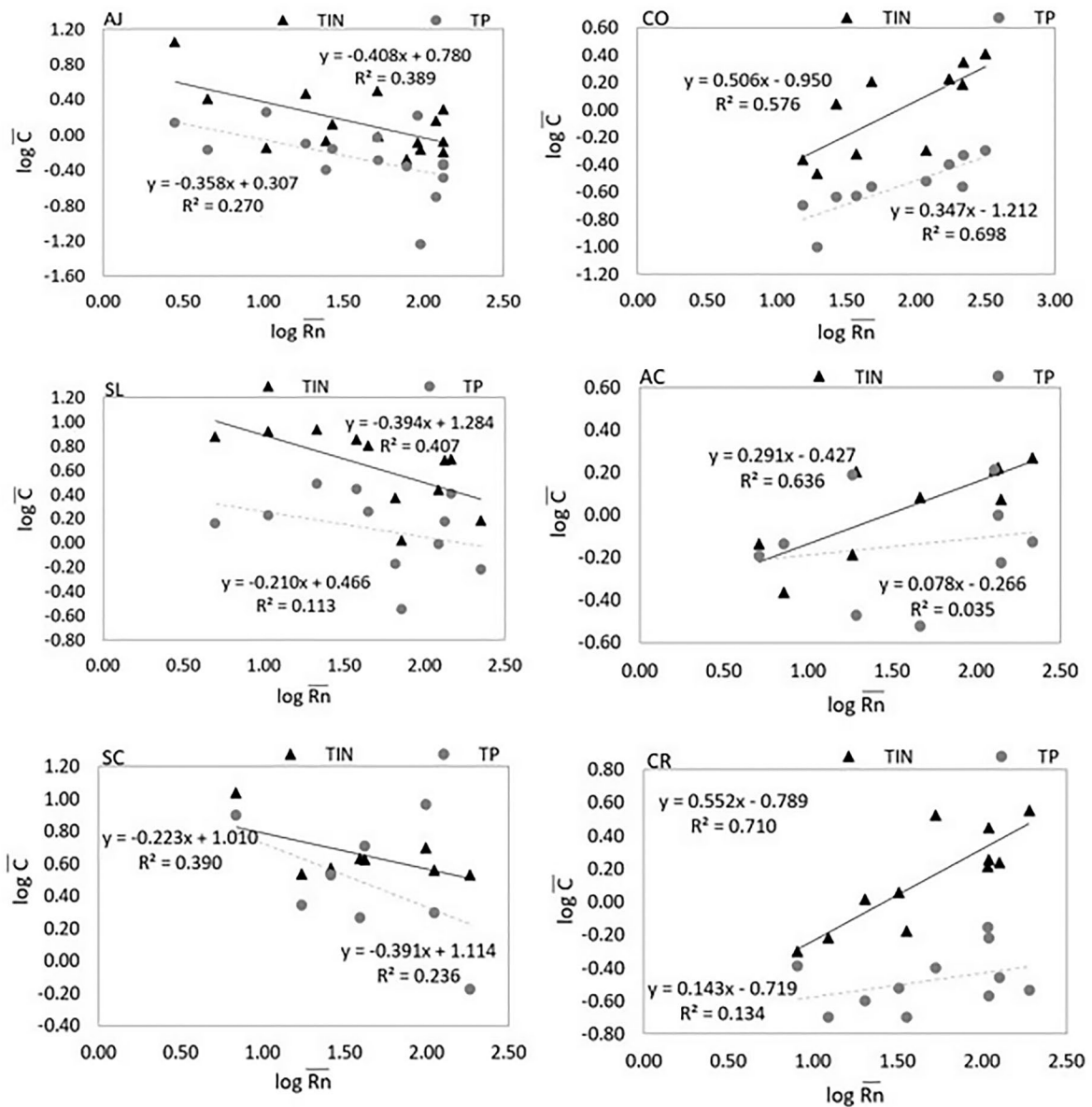


Fig. 6 Linear regression plots for hydrographic regions with correlation significant between rainfall and nutrients. (C, concentration (mg/L); Rn, monthly rainfall; TP, total phosphorus;

TIN, total inorganic nitrogen) (Acarauá (AC), Coreauá (CO), Curu (CR), Alto Jaguaribe (AJ), Salgado (SL), and Sertões de Crateús (SC))

the effect of rainfall is not the major influence on changes in nutrient concentration. These results corroborate that found by Xiao et al. (2023) when defining relationships of predominant variable effects according to the spatial and temporal magnitude of water quality pollution.

Large-scale land use, rainfall, and nutrient concentration

To understand the pattern of demographic distribution and anthropic activities evaluated, Pearson's correlation was performed, shown in Fig. 7. The percentage

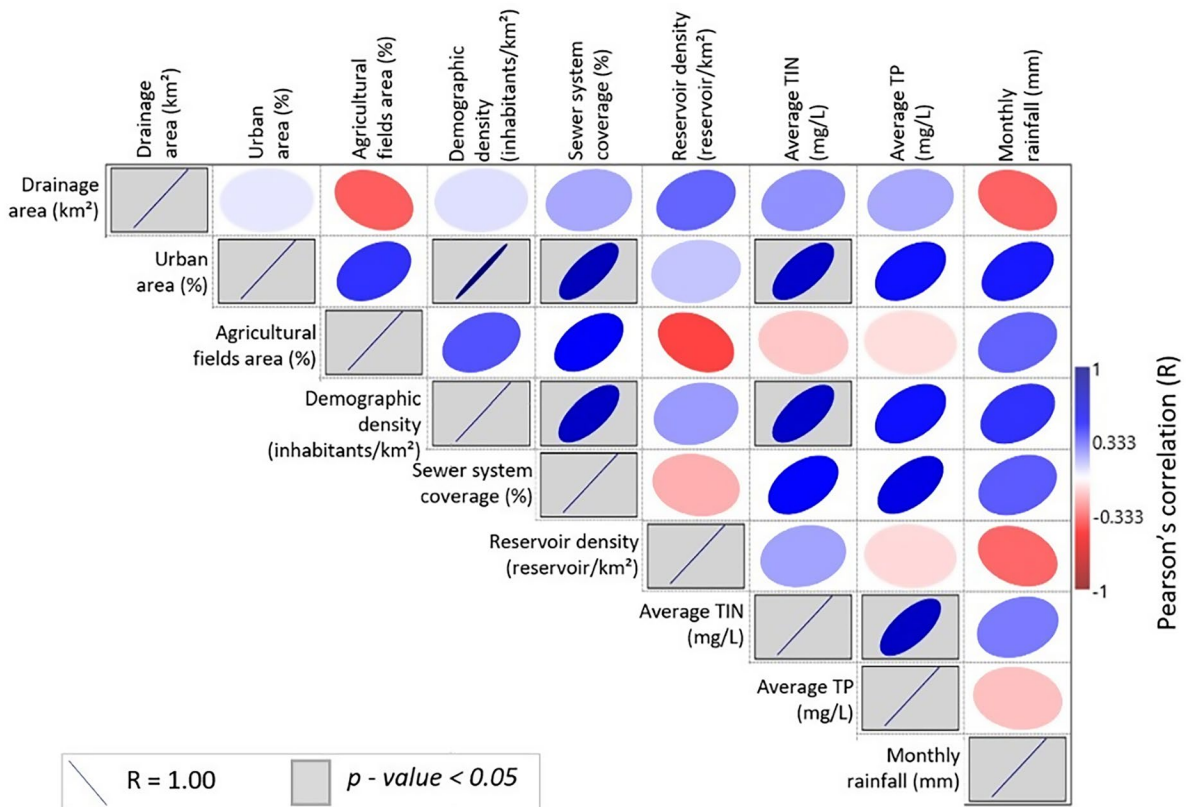


Fig. 7 Pearson's correlation between the variables evaluated considering all hydrographic regions

of the urban areas showed a significant positive relationship with demographic density and with the sewer system coverage. Therefore, most of the population and sewage collection services are in urban locations. The strongest relationships between land use indicators and nutrient concentration were identified for urban area, demographic density and sewer system coverage. Domestic and industrial wastewaters considerably increase nitrate concentrations from upstream to downstream rivers (Shi et al., 2019). In the SL watershed, for example, it is estimated that phosphorus loads from anthropogenic sources to rivers can be more than ten times greater than natural contributions (Paula Filho et al., 2019). This fact may justify a low correlation between precipitation and mean TP concentrations, despite the propensity to dilution. These conditions are similar to some regions in China with high levels of human occupation, where urbanisation ends up being the most influential factor

in water quality (Li et al., 2015; Yang et al., 2016). The increase in TIN and TP in relation to the percentage of urban areas can also be generated by soil sealing. According to Ahiablame et al. (2012), the implementation of permeable pavements and rainwater containment systems in an urban area can reduce phosphorus and nitrogen loads in surface run-off. Urban watersheds with an impermeable surface do not have the capacity to trap phosphorus, so this is exported as biomass or through waste in stormwater run-off (Hobbie et al., 2017; Wang et al., 2014). Furthermore, it should be noted that the size of the riparian buffer is decisive on the different levels of environmental ecological impacts caused by urbanisation and agriculture (Lacher et al., 2019; Xu et al., 2020). Thus, in urban areas, in addition to having greater sources of nutrients for water resources, there is a lower impact attenuation because the riparian buffer is reduced along built-up areas in the study region.

As for the sewer system coverage and its relationship with the concentration of nutrients (Fig. 7), this is explained by the fact that the sewage treatment technologies in the region are mostly at the secondary level, not being able to remove nitrogen and phosphorus (Brazil, 2013; Marangon et al., 2020). Thus, large concentrations of nutrients from wastewater are discharged into water resources (Schliemann et al., 2021; Wang et al., 2015). There was a negative correlation between the reservoir density and the average monthly rainfall. This can be explained by the greater rainfall occurring mostly in the coastal zone and the highest demands for water storage and transfer being supplied by strategic dams in the interior and central areas of the territory (Albiero et al., 2018; Cirilo et al., 2016). A strong positive correlation was found between the number of reservoirs and the drainage area, observing a large number of reservoirs along the Jaguaribe River, the largest and most important river in the study area. In this region, the rivers could be dry for several months, while in a shorter period, in the rainy season and in wet years, high flows were verified. Thus, the population was vulnerable to two issues: the limitations of water supply and maintenance of economic activities, essentially agriculture, and the unpredictability of high flows (Campos, 2015). Therefore, strategic dams were built in places with less accumulated precipitation, high temporal variability of flows, and strategic places for water storage (Campos & Studart, 2008). This finding corroborates the global trend, where the largest numbers of water reservoirs are in regions with more water scarcity, supporting the water supply for 15% of the global population (Mady et al., 2020). However, although strategic reservoirs are well distributed, most small reservoirs were built without any planning by farmers and rural communities since nineteenth century, generating a high-density reservoir network (Araújo et al., 2022; Malveira et al., 2012). The high density of small reservoirs increases vulnerability to dry years, because strategic reservoirs provide more water security during such critical periods, but recover from hydrological drought later when there are many dams upstream (Van Langen et al., 2021).

Regarding the backward stepwise multiple regression on a large spatial scale, the best predictors to TP were the percentage of the sewer system coverage and the monthly average rainfall. These predictors explained 71.1% of the variance in TP concentration.

The coefficient multiple regression (0.843) indicates that there is a very strong direct relationship between the simulated data with predictors and observed data. These results corroborate those of Darwiche-Criado et al. (2015) by associating phosphorus concentrations with urban pollution sources. Untreated wastewater discharges and wastewater treated with technologies that are not effective in removing nitrogen and phosphorus considerably increase the nutrient load in rivers, especially for watershed-scale assessment (Liu et al., 2018). Xia et al. (2016) also found wastewater as one of the main predictors of water quality in a statistical model using rainfall and land use data. Furthermore, the multiple relationship confirms what was discussed earlier for the influence of wastewater on phosphorus concentrations in rivers and on the effect of large-scale rainfall.

The backward stepwise for TIN identified the urban area (%) as a moderate predictor, corroborating with the findings by Cerqueira et al. (2019) for a watershed in the south of the Brazilian Northeast. However, this predictor was only able to explain 21.3% of the variance of the independent variable. The multiple regression coefficient corresponded to 0.461, twofold lower than that identified for total phosphorus. This shows how complex the nitrogen dynamic is in these rivers when evaluating the large-scale. Identifying urban areas as predictors of nutrient concentration is favoured in the watershed scale, because they are pollution hot spots, due to industries and other anthropic activities (Shi et al., 2017; Xu et al., 2020). Moreover, the influence of reservoirs can also limit the application of statistical models to predict the finer effects of land use on water quality (Szatten & Habel, 2020). In this sense, semi-distributed models have been applied to study the influences of other land use on nitrogen concentrations, mainly in the detection of non-point pollution sources (Yang et al., 2016).

The effects of agriculture on water quality are stronger than those of urbanisation depending on the types of crops deployed (Wan et al., 2014). Nevertheless, the low Pearson correlation between the agricultural field area may be due to the fact that most monitoring sites are downstream urban centres, where point source discharges of urban wastewater start to exert greater influence on water quality (Lopes et al., 2021). A fine-scale assessment could be more effective in detecting agricultural

influence on nutrient concentration, as performed by Cheng et al. (2018), Rodríguez-Romero et al. (2018), and Uwimana et al. (2018). Through studies with fine scales, visualisation of the effects of fertilisers and agricultural practices is stronger (Huang et al., 2015). Ammonia concentrations, for example, can be evaluated on broader scales. However, only finer scales detect phosphorus variations in relation to land use (Liu et al., 2017). For this reason, the detection of the effects of agricultural fields may not have been so evident in this paper. In this sense, new water quality monitoring sites in the vicinity of agricultural areas could improve the understanding of the influence of this type of land use.

In the most urbanised watershed (MT), the relationships between nutrients and Rn were not representative, as well as in MJ and BJ. For these watersheds, we consider the effect of rainfall in a linear correlation assessment as marginal. Hence, on the evaluated scale, precipitation does not have a major effect on changes in nutrient concentration.

Conclusions

This paper investigated the relationship between rainfall and nutrient transport in semiarid hydrographic regions in Brazil, considering indicators of anthropogenic interference. The results revealed that the effect of rainfall can be marginal, inverse, or positive for the increase of nutrient concentrations. Hence, there is a more efficient transport of nutrients from the catchment to the rivers when there is greater intensity of rainfall and fewer upstream reservoirs. This transport occurs more quickly for TIN than TP. The inverse relationship between rainfall and nutrients occurs when the demographic density is higher and there are a greater number of reservoirs in the watershed, or when there is strong interference from point source pollution.

On a large scale, the most representative predictors of TP concentrations were the sewer system coverage and the monthly rainfall. On the other hand, for TIN, the most representative predictor was the percentage of the urban areas. This reveals how much urbanisation and the lack of wastewater treatment are related to nutrient concentrations on a large scale. A natural aspect also presented an important

relationship — the accumulated total precipitation, demonstrating that even under the same climatic conditions, the distribution of rainfall influences the hydrological responses in water quality.

The findings of this study are essential for the understanding of nutrient concentrations in the rainy season, which may guide water governance. In places with increased TP and TIN concentrations, during the rainy season, actions to control erosion, protect river banks, and natural sediment barriers can be prioritised. In cases where precipitation did not have a great influence, the control of point sources of pollution is even more urgent. In this way, adaptative and decentralised management water resources should be more effective for controlling pollution and improving water quality in this region. It is noteworthy that the location of river sites for monitoring water quality may have influenced the assessment. An expansion of monitoring sites close to agricultural areas would be necessary to investigate the real impact of crops on the concentration of nutrients in river waters, which can be carried out in future research. Moreover, monitoring of the total nitrogen in rivers should enable future research, especially those related to nitrogen mass balance.

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Availability of data and materials Data will be made available on reasonable request.

Declarations

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