Coastal erosion in the Paraíba do Sul River basin: a preliminary analysis of land use and sedimentary dynamics

Erosão costeira na Bacia do Rio Paraíba do Sul: uma análise preliminar do uso da terra e da dinâmica sedimentar

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ABSTRACT

The Paraíba do Sul River basin supplies major urban centres, such as São Paulo and Rio de Janeiro, and has been significantly impacted by urbanisation and multiple water uses. Over time, water demand has increased for the construction of hydropower dams and water-transfer systems. This research preliminarily examines how land-use changes and hydrometeorological trends have influenced sediment transport. We conducted an integrated analysis using sediment data from the National Water Agency (ANA) and land use data (1985–2021) from MapBiomas. Results show significant declines in river discharge and sediment load, likely due to reduced soil erosion from land-use changes, increased water demand, and reservoir flow regulation. Although coastal erosion at the river mouth is worsening, its causes cannot be attributed to basin disturbances, as coastal processes and climate change may also influence it. Given data limitations, the findings remain preliminary and require further observational and modelling studies.

Keywords: Trend analysis. Pluviometry. Fluviometry. Land use. Sediment transport.

RESUMO

A Bacia do Rio Paraíba do Sul abastece grandes centros urbanos, como São Paulo e Rio de Janeiro, e tem sido significativamente afetada pela urbanização e pelos múltiplos usos da água. Ao longo do tempo, a demanda por água impulsionou a construção de barragens hidrelétricas e de sistemas de transferência de água. Esta pesquisa investiga, de forma preliminar, como as mudanças no uso da terra e as tendências hidrometeorológicas influenciaram o transporte de sedimentos. Realizamos uma análise integrada utilizando dados de sedimentos da Agência Nacional de Águas (ANA) e dados de uso da terra (1985-2021)

do MapBiomas. Os resultados mostram declínios significativos na vazão fluvial e na carga de sedimentos, provavelmente relacionados à redução da erosão do solo decorrente de mudanças na cobertura do solo, ao aumento da demanda hídrica e à regulação do fluxo por reservatórios. Embora a erosão costeira na foz do rio esteja se agravando, suas causas não podem ser atribuídas a perturbações na bacia, visto que processos costeiros e mudanças climáticas também podem influenciá-la. Devido às limitações dos dados, as conclusões permanecem preliminares e requerem estudos adicionais de observação e modelagem.

Palavras-chave: *Análise de tendência. Pluviometria. Fluviometria. Uso da terra. Transporte de sedimentos.*

1 INTRODUCTION

Located in Southeast Brazil, the Paraíba do Sul River basin is one of the most strategic of Brazil as a source of water supply for a large population, including the largest country metropolis: São Paulo and Rio de Janeiro. The basin is highly disturbed by urbanisation and industrialisation, is degraded, and experiences intensive use of the water resource for agriculture, industry, and supply, in addition to large discharges of sewage effluents that impact both the quality and quantity of its water (Demanboro, 2015).

According to Neves and Vilanova (2021), the Paraíba do Sul River Basin can be treated as a hydraulic system, since its waters transcend the limits of the basin through to water transfers: to the Metropolitan Region of Rio de Janeiro through the transposition to the Guandu River carried out in the 1950s, which diverts around (100 m³/s), and more recently for the São Paulo Metropolitan Region through the Cantareira System (5 m³/s), accounting for 80% of the state's water supply and 20% of energy production (Ferreira, 2008; Formiga-Johnsson; Britto, 2020, Vasconcelos, 2019).

The region at the mouth of the Paraíba do Sul basin has a deltaic pattern, characterised by a fan with various channels formed by sediment accumulated from river transport, which is constantly shaped by tides, waves, currents, and the river itself. This region suffers serious coastal erosion and sea intrusion, which have been attributed to several factors, including coastal circulation, reduced sediment supply from the continental shelf, and rising sea levels (Ribeiro *et al.*, 2006).

A similar behaviour is observed at the mouth of the São Francisco River in the Northeast of Brazil. In this case, Oliveira *et al.* (2003) concluded that the basin's high regulation affected river discharges and sediment transport, reducing sediment loads and velocity in the lower São Francisco. Recently, Fagundes *et al.* (2023) reported a reduction in sediment flow in South American rivers due to deforestation, hydropower expansion, and the construction of water reservoirs. As a result, siltation of the river increased, with the finer sediment transported and the coarser sediment deposited in the river channel, causing impacts on the middle course and reducing sediment transport at the mouth.

In the case of the Yellow River in China, Chu (2014) showed that drastic changes at the mouth are associated with a reduction in sediment load due to the presence of dams and reservoirs, followed by water and soil conservation practices, water abstraction for consumption and sedimentation in the channel, which causes sedimentation, as well as in other characteristics of the river.

In this context, a study by Lämmle *et al.* (2022), based on chemical analyses of water and sediments, concluded that coastal erosion at the mouth of the Paraíba do Sul is driven by anthropogenic uses throughout the entire basin, particularly sediment retention by the main basin reservoirs.

It is clear, therefore, that highly anthropized basins such as the Paraíba do Sul River basin can have changes in sediment load due to the reduction in stream velocity as a result of dams, as well as changes in land use due to inadequate management practices in rural and urban environments (Guo *et al.*, 2018; Neves *et al.*, 2021; Oliveira *et al.*, 2023).

In previous studies, Molisani *et al.* (2006) reported that water transfer to the Guandu River increased sediment input to the Guandu Basin by 28%, thereby reducing sediment load at the mouth of the Paraíba do Sul. Therefore, this study aims to conduct a preliminary analysis of the influence of land-use changes and hydro-meteorological trends on sediment input and their possible relationship with the negative impacts observed in the estuary region.

Understanding the causes of this problem is fundamental, given that these changes have caused negative impacts on the water supply in the municipality of São João da Barra, located at the mouth, causing changes in aquatic life (fauna and flora) and mangroves, as well as the destruction of houses, buildings, and entire streets, businesses, among other physical structures.

2 MATERIALS AND METHODS

2.1 MATERIALS

2.1.1 STUDY AREA

The Paraíba do Sul River is formed by the confluence of two rivers, the Paraibuna and the Paraitinga, in the Serra da Bocaina at an altitude of 1800m, flowing into the north of Rio de Janeiro, at Atafona beach in the town of São João da Barra/RJ (Gripbsul, 2022).

To the north, the river basin lies between the Grande (Paraná basin) and the Doce (eastern Brazilian system) rivers via the Serra da Mantiqueira; to the south, the Serra do Mar. Figure 1 shows the location of the basin, and the main river Paraíba do Sul and its main tributaries: Paraibuna, Paraitinga, Paraibuna (which rises in the state of Minas Gerais), Pomba, and Muriaé.
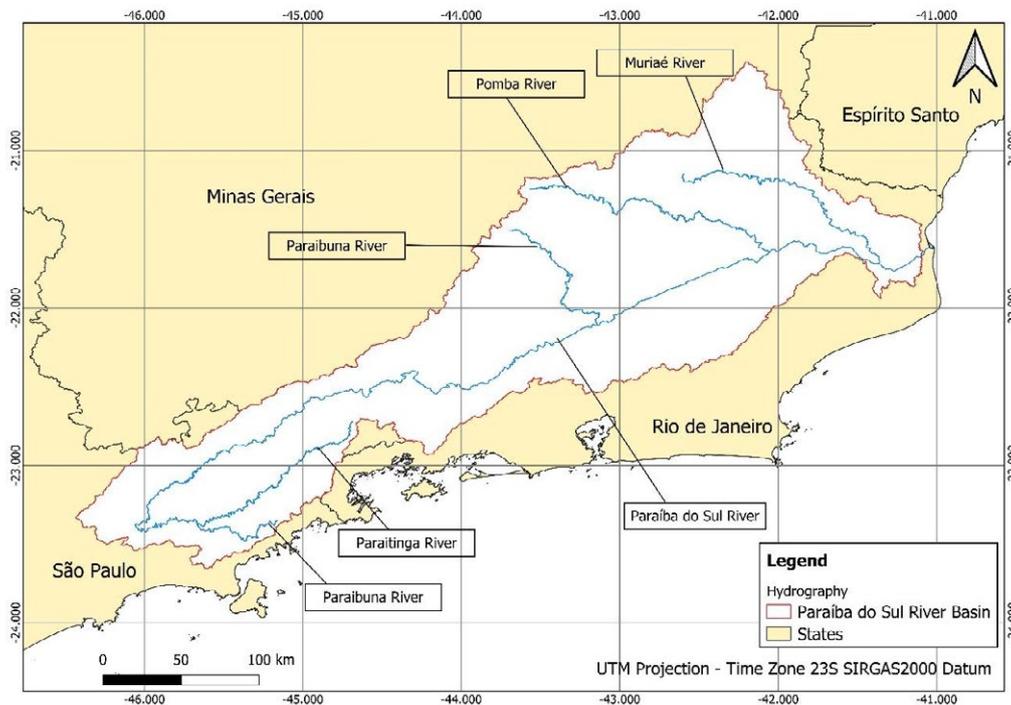

Figure 1 – Paraíba do Sul River Basin and its main tributaries.

Source: Adapted from the National Water Agency (ANA) and Brazilian Institute of Geography and Statistics (IBGE), 2023

The basin's drainage network covers approximately 62,000 km2. In terms of water consumption, Rio de Janeiro uses 66%, São Paulo 24% and Minas Gerais only 10%.

The region at the mouth of the Paraíba do Sul basin (Figure 2) is affected by severe coastal erosion, which has destroyed infrastructure along the coast and unsettled local communities.

Figure 2 – Changes in the Foz do Paraíba do Sul coastal area over the decades. The red line highlights changes in the coastal area adjacent to Atafona/RJ, where the narrowing of the sand strip near the river mouth is clearly visible and is associated with erosion advancing over urban structures.

Source: Adapted from Google Earth, 2025

Oliveira (2015) carried out a study using satellite images over a historical series and identified processes of regression, i.e., sediment removal. On the other hand, in the areas furthest from the mouth, the process of progradation was observed, with the deposition of sediment and the widening of beaches.

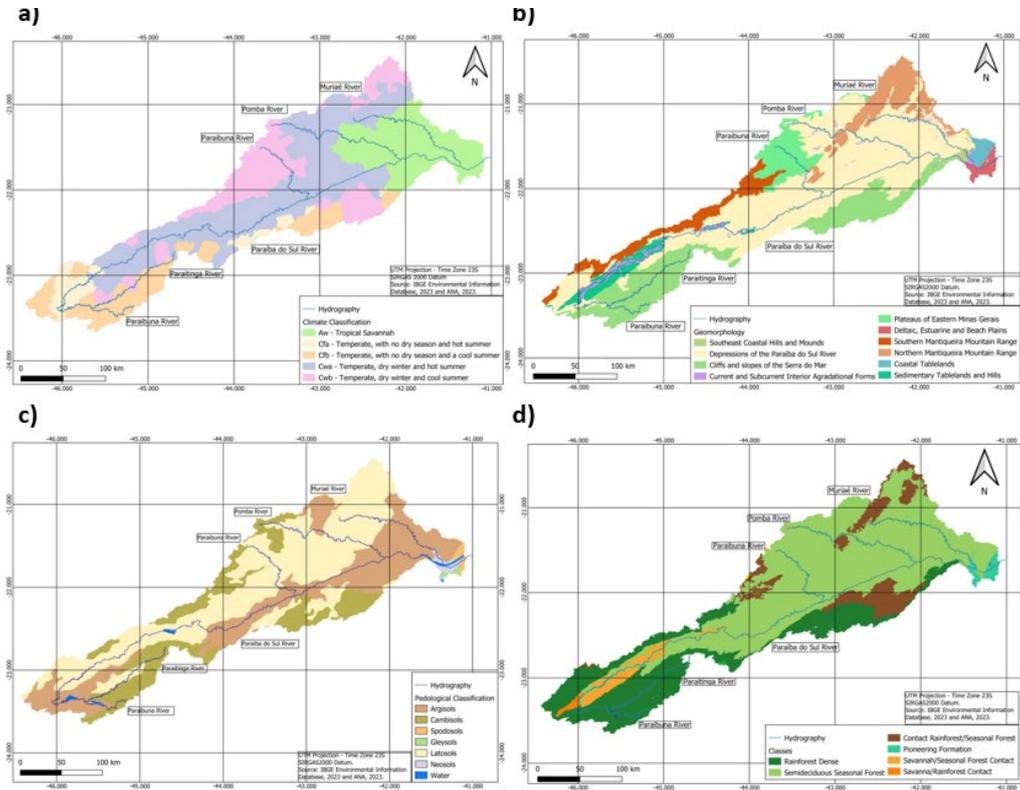## 2.1.2 CLIMATOLOGY, GEOLOGY, PEDOLOGY, AND VEGETATION

Figure 3 – Climatological (a), Geological (b), Pedological (c), and Vegetation maps of the PSRB.

Source: Adapted from Environmental Database and Information (BDiA) – IBGE, 2025

Rainfall climatology of the basin is very diverse (Figure 3a), with mountainous regions in the Serra da Mantiqueira, Serra da Bocaina and Serra do Mar, with annual rates above 1500 mm, reaching up to 2000 mm per year, at lower altitudes and closer to the river channel the rates are close to 1000 mm per year (Brasiliense *et al.*, 2020). Rainfall in the basin is concentrated between October and March, accounting for 80% of the annual rainfall (Da Silva *et al.*, 2024; Marengo; Alves, 2005).

Annual average temperature ranges between 16ºC and 22ºC, with a wide variety of characteristics: in the mountainous regions to the north of the basin, with an average of 10ºC, and at the mouth of the Paraíba do Sul River, with an average of 32ºC (Brasiliense *et al.*, 2020, Ceivap, 2021).

The soil types presented here were defined on the Brazilian Soil Map of the Brazilian Agricultural Research Corporation (Embrapa, 2018), and the classification generated for the study basin shows a dominance of argisols and latosols.

2.2 METHODS

2.2.1 DATABASE

In this study, an integrated methodological approach was used to investigate the relationships among rainfall variability, river discharge dynamics, and sediment transport processes in the Paraíba do Sul River. The methodology was organised into four complementary steps: (1) data acquisition and qualification, (2) temporal and spatial characterisation of hydroclimatic conditions, (3) sediment transport analysis, and (4) integration of results for hydrosedimentary interpretation of the basin.

Hydroclimatic and sediment transport data were obtained from the National Water Agency (ANA/ Hidroweb), the Brazilian Geological Survey (CPRM), the São Paulo Department of Water and Electric Power (Daee/SP), the Minas Gerais Institute of Water Management (IGAM/MG), the National Meteorological Institute (Inmet), the National Centre for Monitoring and Alerting of Natural Disasters (Cemaden), among other public and private partners.

Three types of datasets were considered:

- Rainfall data: daily and 24-hour accumulated;

- Fluviometric data: discharge, and

- Sedimentometric data: suspended and bedload sediment concentration.

For the study, only stations with historical rainfall series longer than 30 years and fluviometric and sedimentometric series longer than 15 years, with less than 10 % missing data, were considered. The number of stations used is shown in Table 1.

Table 1 – Number of available stations and data periods.

Variables	Average	Used	Period
Rainfall	711	168	1940 to 2022
River flow	451	45	1940 to 2022
Sedimentation	80	6	1989 to 2021
Rainfall Accumulation for 24h	47	47	2014 to 2021

Source: The authors, 2025

Statistical trends in the series were detected using the Mann-Kendall test (Hamed, 2009; Leite *et al.*, 2023; Mallick *et al.*, 2021), a nonparametric test. This method has been widely used for hydro-meteorological and sedimentological analyses and has been described in several studies (Bernal *et al.*, 2006; Marengo; Alves, 2004; Oliveira *et al.*, 2021). In this study, a 5% significance threshold was accepted.

Because the available load sediment series includes data collected at irregular intervals and frequent significant gaps due to missing data, we did not attempt to identify breakpoints in the trends.

2.2.2 LAND USES

The assessment of land use changes in the Paraíba do Sul River basin was conducted using a methodological framework that integrates remote sensing products, data aggregation procedures, spatial analysis, and temporal comparisons of landscape transformation.

Raw data were obtained from the MapBiomas Project – Collection 7, using the Google Earth Engine Toolkit (Gorelick *et al.*, 2017; Santos *et al.*, 2025). The temporal snapshots selected for analysis were 1985 (baseline year) and 2021 (the most recent year available in the dataset).

Vegetation types were aggregated into 5 large groups, which are Forest (forest formation, savannah, mangrove, and wooded restinga), Non-Forest Natural Formation (flooded field and marsh area, grassland formation, apicum, rocky outcrop, herbaceous restinga, and other non-vegetated areas), agriculture (pasture, agriculture, forestry, and mosaic of uses), non-vegetated area (beach, dune and sandy area, urbanized area, mining and other non-vegetated areas), and body of water (river, lake or ocean and aquaculture). We also verified changes in vegetation and land-use classes between 1985 and 2021. Changes over the study period were analysed using QGIS.

3 RESULTS AND DISCUSSION

Changes in land use were observed in the basin, comparing 1985 and 2021. In 1985, the forest area accounted for 25.01% of the territory, and another 52.95% was pasture. Meanwhile, in 2021, 27.86% of the area was forested, while 49.94% was occupied by pasture (Figure 4).
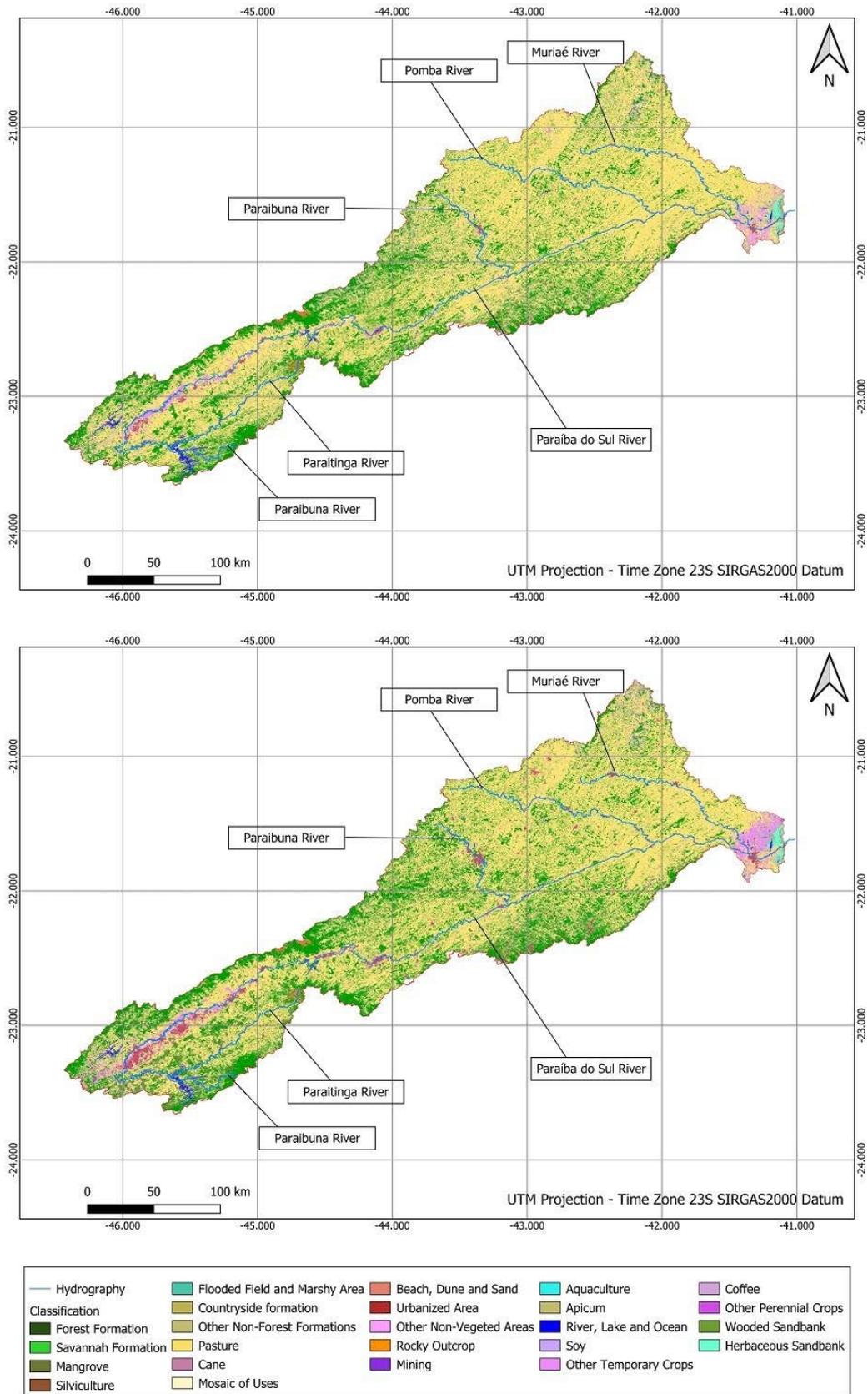
Figure 4 – Land use map of the Paraíba do Sul River basin in 1985 (top) and 2021 (bottom).

Source: ANA and MAPBIOMAS,2023

Table 2 shows the changes observed in these classes, where positive signs show an increase and negative signs a decrease in the established class.

Table 2 – Land-Use Changes.

Classes	Land Use Comparison 1985-2021 (%)
Forest	+ 10.43
Non-Forest Natural Formation	+0.10
Agriculture	- 5.82
Non-vegetated Area	+ 55.90
Water	- 11.81

Source: MapBiomas, 2025

It is important to note that the percentages shown in Table 2 are comparative between the use of the class in 1985 and 2021. The increase in the non-vegetated area is associated with urban expansion. The MapBiomas Project indicates that 25% of the basin's total area has changed to this class.

A total of 168 rainfall stations were analysed, of which 146 showed no significant trends, another 14 showed positive trends, and only 8 showed negative trends (Figure 5a). The absence of a trend in almost 87% of the stations indicates that the rainfall regime in the basin over the historical periods analysed has not undergone major changes, which is corroborated by the studies of Oliveira *et al.* (2003) and Santana *et al.* (2020).

Regarding discharges, 45 stations were analysed: 17 showed no significant trend, 28 showed a downward trend, and none showed an upward trend (Figure 5). More than 60% of the gauging stations showed a downward trend in flows, which may indicate the influence of land-use changes in the basin and the regularisation of flows due to reservoirs.
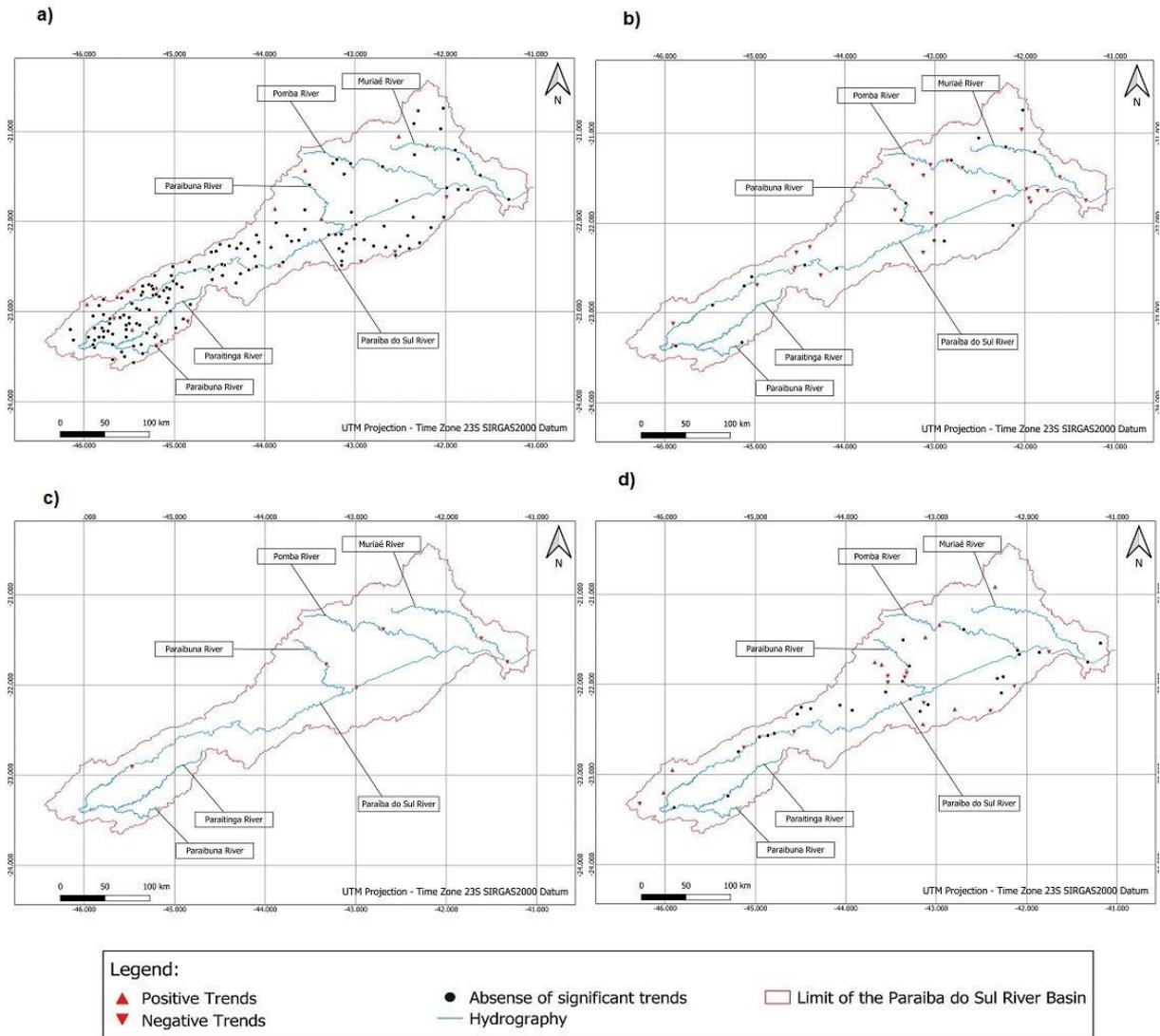
Figure 5 – Statistical trends in the Paraíba do Sul River for rainfall (a), river discharge (b), Sediment load (c), and daily rainfall (d) over the periods indicated in Table 1.

Source: ANA, 2023

Regarding data integrity, only 6 stations with relevant quantities were obtained, all of which showed a downward trend, in agreement with the trends observed at the large majority of sediment discharge stations (Figure 5c).

Downward trends are clearly evident in Figure 6, which shows discharge and sediment load time series for the period 1989-2018 along the river main stem at 3 stations: Pindamonhangaba/SP, Anta/RJ, and Campos/RJ. It is important to note that the negative trends of sediment loads in Pindamonhangaba station are driven by decreasing concentration of sediments, while in the case of both Anta and Campos stations, they are a combination of decreasing both sediment and discharge values. In other words, the negative trends in sediment load in the lower basin are exacerbated by reduced discharges. It is important to emphasise that the historical time series used in this analysis includes both dry and wet periods, with continuous measurements throughout the monitoring record. This minimises the risk of drawing conclusions influenced by isolated or atypical climatic conditions.
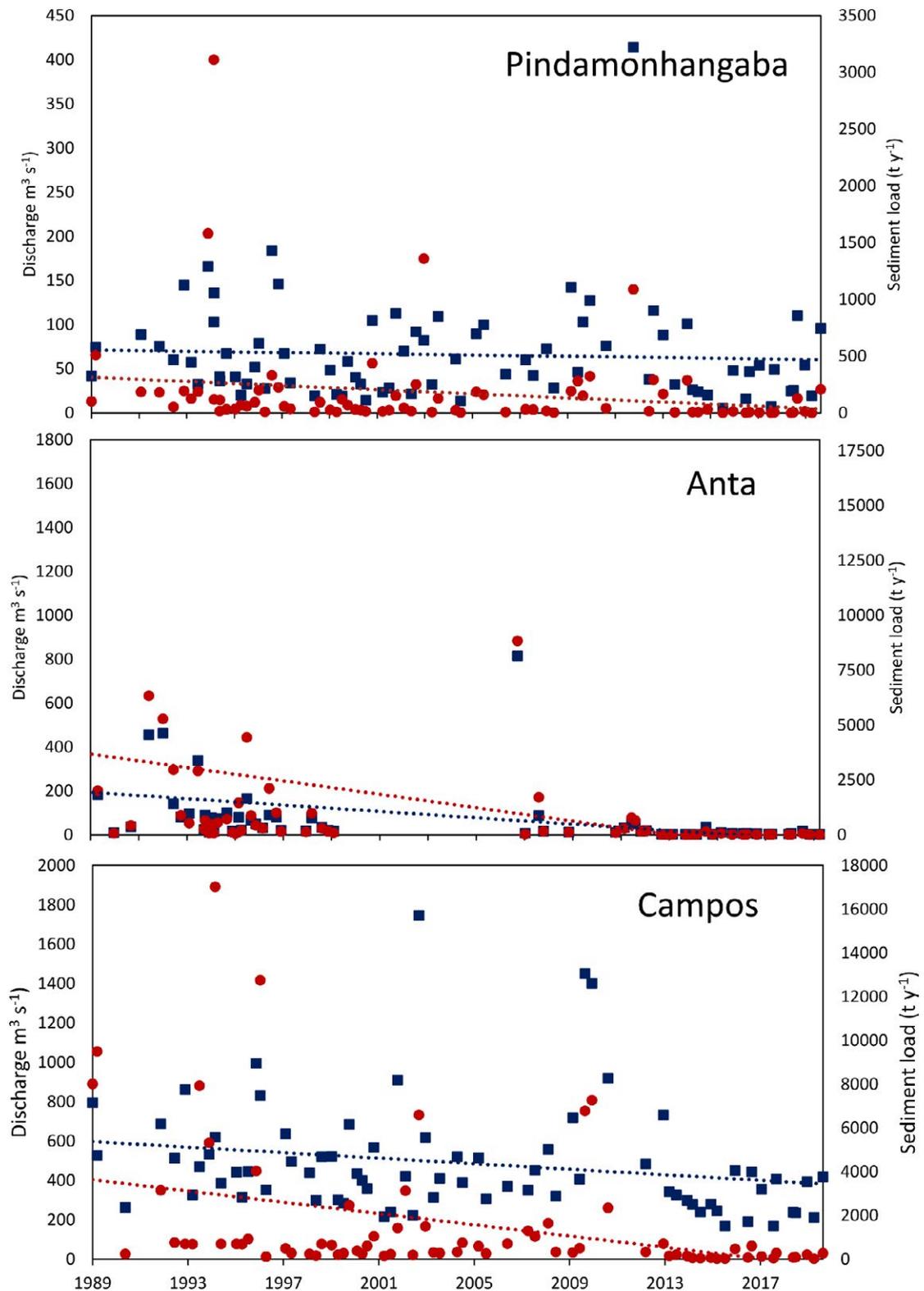
Figure 6 – Discharge (blue squares) and sediment load (red circles) along the Paraíba do Sul River over the period 1989-2018.

Source: The authors, 2025

Table 3 illustrates the variation in sediment load based on different time slices along the main river for the gauging stations of Figure 6. Comparing data from previous years shows a progressive decrease in the sediment load. Reductions are significant in all analysed periods for both sediment concentration and load, ranging from -2 to -4% per year for sediment concentration and up to -4% per year for sediment load.

Table 3 – Sediment load along the Paraíba do Sul River over the period 1994-2018

Period	Pindamonhangaba		Anta		Campos	
	Concentration (mg/L)	Load (ton/ year)	Concentration (mg/L)	Load (ton/ year)	Concentration (mg/L)	Load (ton/ year)
1994-1995	53.67	67.45	12.55	207.80	60.43	743.55
1999-2000	28.39	29.64	-	-	49.04	668.79
2017-2018	3.66	3.09	4.95	15.15	12.60	524.90

Source: The authors, 2025

In addition, Jordão and Vinzon (2017) estimated that water transfer to the Guandu River removes approximately 51 tons of sediment per year from the Paraíba do Sul. Assuming an average diverted flow of 100 m3/s, this implies an average concentration of 16.2 mg/l, slightly greater than the values of concentration of 12.6 mg/l observed in Campos over the period 2017-2018. In terms of sediment load, we can estimate that the amount of sediment diverted to the Guandu System represents approximately 10% of the total load at Campos during 2017-2018. However, because the water transfer to the Guandu System was implemented in the 1950s, the reduction of sediment load cannot be attributed to the diversion of the Guandu system.

Moreover, most of the cascade of dams was inaugurated during the 1950s and 1960s, and therefore, the trends in Table 3 are not due to the initial filling of reservoirs. Consequently, the more likely explanation for the sediment trends observed in the basin is a reduction in flows, presumably due to increasing consumption, since no trends were observed at rainfall stations, in combination with a reduction in erosion related to land uses (increased afforestation and soil conservation).

In addition, the river is being regularised by the dam cascade system. Controlled flows are associated with increased sedimentation along the river course. Because periodic floods promote sediment transport and more regular attenuation attenuates inundation pulses, it is clear that controlled flows have altered the basin-wide sediment balance.

A recent study by Lämmle *et al.* (2022), using chemical analysis of sediment and water at the river mouth, concluded that sediment capture by the cascade of reservoirs is the main factor triggering coastal erosion and, consequently, morphological changes at the river mouth. Although sedimentation in reservoirs does play a role in sediment imbalance at the river mouth, other factors, such as reduced flow and changes in land use, are likely to contribute to the process. The analysis of the series supports the conclusion of this study, which shows that the negative trends over the period 1989-2018 are well beyond the construction and filling of the large reservoirs of the basin and after the construction of the Guandu water transfer. In addition, we have not investigated other effects, such as the increased sea levels associated with global warming, which can also play a role in coastal erosion.

4 CONCLUSION

It is concluded that the decrease in sediment load in the basin can be explained by several factors including the increased regularization of the river, negative trends in discharge; and a reduction of

sediment concentration due to a combination of reducing flow affecting sediment transportation capacity; and changes in land use within the basin, since areas of pasture and agriculture have become urban, secondary vegetation and secondary forested areas.

The coastal erosion at the mouth of the Paraíba do Sul River has become increasingly severe over the years. Therefore, the decrease in sediment in this deltaic mouth is a factor that influences the coastal dynamics. However, it cannot be concluded that anthropogenic disturbances within the river basin are entirely responsible for the erosion, since these effects can be exacerbated by rising sea levels and changes in currents driven by climate change, which were not analysed in this study. Therefore, more detailed studies are necessary to separate the effects of coastal erosion and the reduction of river sediment load.

Given that this study is the first assessment of a complex process and that the number of stations with sediment data is limited and spans only a relatively short period (1989-2018), the conclusions are preliminary. Further evidence based on observation and modelling is needed to confirm the main findings of this study.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors declare that no generative AI or AI-assisted technologies were used in the creation, writing, or editing of this manuscript.

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