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Quantification of suspended sediments in the watershed of the Paiva Castro Reservoir, Juqueri River, southeastern state of São Paulo

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ABSTRACT

This study presents the results of field surveys regarding flow measurements, water collection and suspended sediment samples, laboratory analyses (grain-size distribution, suspended sediment concentration, and total dissolved solids), and calculations of suspended sediment load in the watershed of the Paiva Castro Reservoir, Mairiporã, SP. The activities were conducted from October 2023 to December 2024, comprising 21 monitoring campaigns. Five sediment monitoring stations were defined along the Juqueri River. Measurements involved flow gauging using an acoustic Doppler device (ADCP RS-5) and collection of suspended sediments using a DH-48 sampler, in addition to laboratory analyses of suspended sediment concentration, particle size, and total dissolved solids. The equal-width increment (EWI) method was used, allowing detailed vertical and cross-sectional sediment distribution data. The results highlight the spatial and temporal variability of suspended sediment concentrations, which is essential for understanding erosion processes and for planning preventive and corrective actions to mitigate reservoir siltation.

Keywords: hydrosedimentology, solid discharge, total dissolved solids.

Quantificação dos sedimentos em suspensão na bacia hidrográfica do reservatório Paiva Castro, Rio Juqueri, sudeste do estado de São Paulo

RESUMO

Este trabalho apresenta os resultados dos levantamentos de campo com relação às medições de vazões, coletas de amostras de água e sedimentos em suspensão, análises laboratoriais (granulometria e concentração de sedimentos em suspensão e sólidos totais dissolvidos) e cálculos da descarga sólida em suspensão na bacia hidrográfica de drenagem do reservatório Paiva Castro, Mairiporã, SP. As atividades ocorreram entre outubro de 2023 e dezembro de 2024, compreendendo 21 campanhas de medição e amostragem. Foram definidas cinco estações sedimentométricas distribuídas ao longo do Rio Juqueri. As medições envolveram vazão com equipamento acústico Doppler (ADCP RS-5) e coleta de sedimentos em suspensão com amostrador DH-48, além de análises laboratoriais de concentração de sedimentos em suspensão, granulometria e sólidos totais dissolvidos. Utilizou-se o método de amostragem por igual incremento de largura (IIL), obtendo dados detalhados da distribuição vertical e transversal dos sedimentos. Os resultados destacam a variabilidade espacial e temporal da concentração dos sedimentos em suspensão, fundamental para o entendimento dos processos erosivos e para planejamento de intervenções preventivas e corretivas visando mitigar o assoreamento do reservatório.

Palavras-chave: descarga sólida, hidrossedimentologia, sólidos totais dissolvidos.

1. INTRODUCTION

This study provides essential information for addressing problems such as reservoir siltation, changes in river cross-sections, and the deterioration of water quality. To this end, field data collection becomes indispensable. According to Paiva *et al.* (2000), understanding sediment input in watersheds is extremely important for the planning and management of water resources. Such information is fundamental for the design and operation of hydraulic structures, significantly influencing the implementation and maintenance costs of these systems.

Studies in the Cantareira System and nearby Southeast basins show event-driven suspended-sediment loads and attenuation toward reservoir forebays, consistent with forebay trapping. At Paiva Castro and adjacent Cantareira reservoirs, researchers report longitudinal gradients and contaminant accumulation in sediments and biota, evidencing deposition zones near the forebay (Beghelli *et al.*, 2020; Cardoso-Silva *et al.*, 2015). In the international context, suspended sediments are closely linked to water-quality degradation and increased treatment costs, which underscores the need for robust monitoring programs and time-series load estimation (Morris and Fan, 1998; Rasmussen *et al.*, 2009).

The experimental area selected for the development of this study is the drainage basin of the Paiva Castro Reservoir, which is part of the Cantareira Water Supply System, located north of the municipality of São Paulo. This basin is strategically important for the water security of the São Paulo Metropolitan Region. Globally, reservoir longevity is threatened by progressive storage loss due to siltation, motivating evidence-based sediment management from planning through operation (Morris and Fan, 1998).

Modern hydrosedimentological monitoring integrates: (i) depth-integrating sampling with cross-sectional compositing (e.g., the USGS Equal-Width Increment method); (ii) discharge measurements using acoustic Doppler current profilers (ADCP) under international guidance; and (iii) surrogate methods (e.g., continuous turbidity) calibrated to suspended-sediment concentration (SSC) to compute time-series concentrations and loads (Edwards and Glysson, 1999; ISO, 2021; Rasmussen *et al.*, 2009). Combining these techniques improves temporal resolution and reduces uncertainty, particularly during storm events that account for a disproportionate share of annual sediment yield (Rasmussen *et al.*, 2009).

This paper presents the techniques used to monitor and assess the evolution of suspended sediment load in the Paiva Castro Reservoir watershed, Juqueri River, during the period from October 16, 2023, to December 13, 2024, covering a total of 21 monitoring campaigns. It also presents the results of field surveys, including flow measurements, collection of water and suspended sediment samples, laboratory analyses (grain size distribution, suspended sediment concentration, and total dissolved solids), and the calculation of suspended sediment discharge during the monitoring period.

The monitoring was conducted systematically, with flow measurements and suspended sediment sampling carried out at different frequencies throughout the year. Whenever possible, the campaigns were conducted biweekly during the rainy season (October to March) and monthly during the drier months (April to September), thus covering a complete hydrological cycle. This sampling design captures spatiotemporal variability in SSC and discharge, including high-energy storm events that are critical to annual sediment balances and reservoir siltation risk (Rasmussen *et al.*, 2009; Morris and Fan, 1998).

2. MATERIAL AND METHODS

The methodological procedures followed the Sedimentometric Practices Guide (Carvalho *et al.*, 2000; Carvalho, 2008), which provided support for defining the monitoring locations, sampling frequency, measurement methods, sampling techniques and equipment types, as well as the types and methods of analysis and the calculation of suspended sediment concentration and load. The monitoring of suspended sediment transport was carried out at five sedimentometric stations distributed along the drainage basin of the Paiva Castro Reservoir, on the Juqueri River, where the data were systematized and interpreted.

The study area is located in the southeastern portion of the State of São Paulo (Figure 1) and lies within the drainage basin of the Paiva Castro Reservoir, along the Juqueri River, in the municipality of Mairiporã, São Paulo. The main access from the city of São Paulo is via the Fernão Dias highway (BR-381), approximately 70 km from the capital.

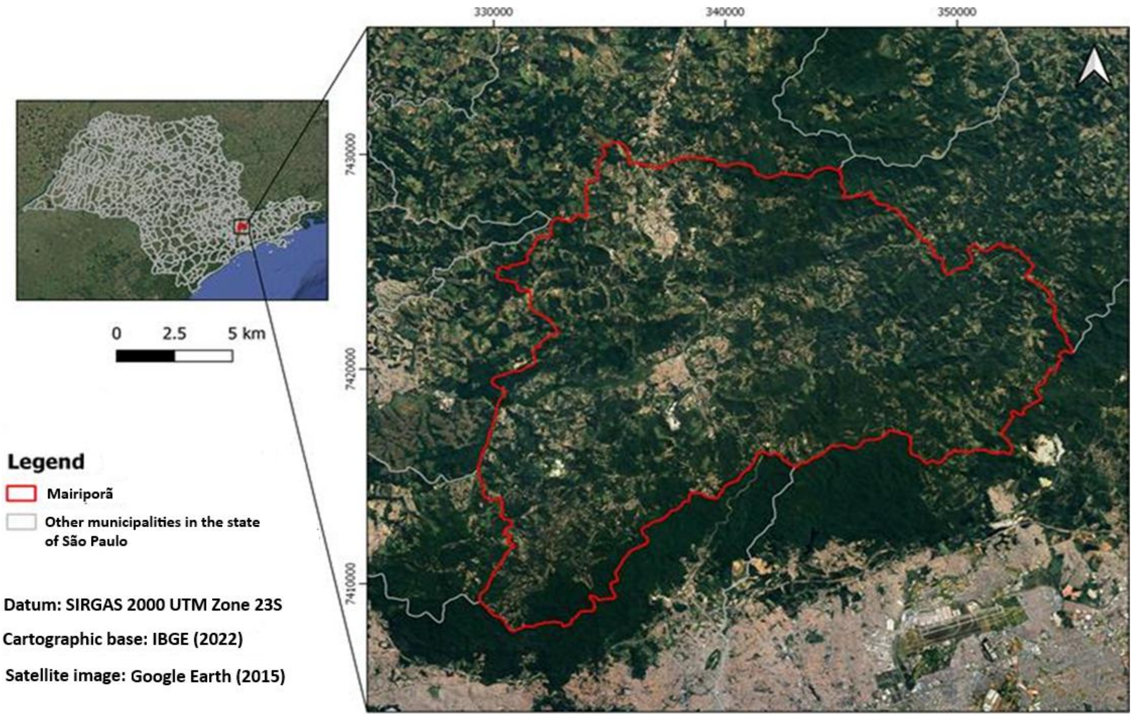

Figure 1. Location of the study area, Mairiporã, SP.

To select the sedimentometric sections, 1:50,000 scale topographic maps from IBGE (1972) were used. After outlining the maximum filling elevations of the reservoir, the following sections were determined: one section downstream from the Paiva Castro Reservoir dam, designated SJY-1 (P1), and four significant sections along the Juqueri River up to the tunnel outlet (Tunnel 5, at the border between Mairiporã and Nazaré Paulista), designated SJY-2 (P2), SJY-3 (P3), SJY-4 (P4), and SJY-5 (P5) (Figure 2).

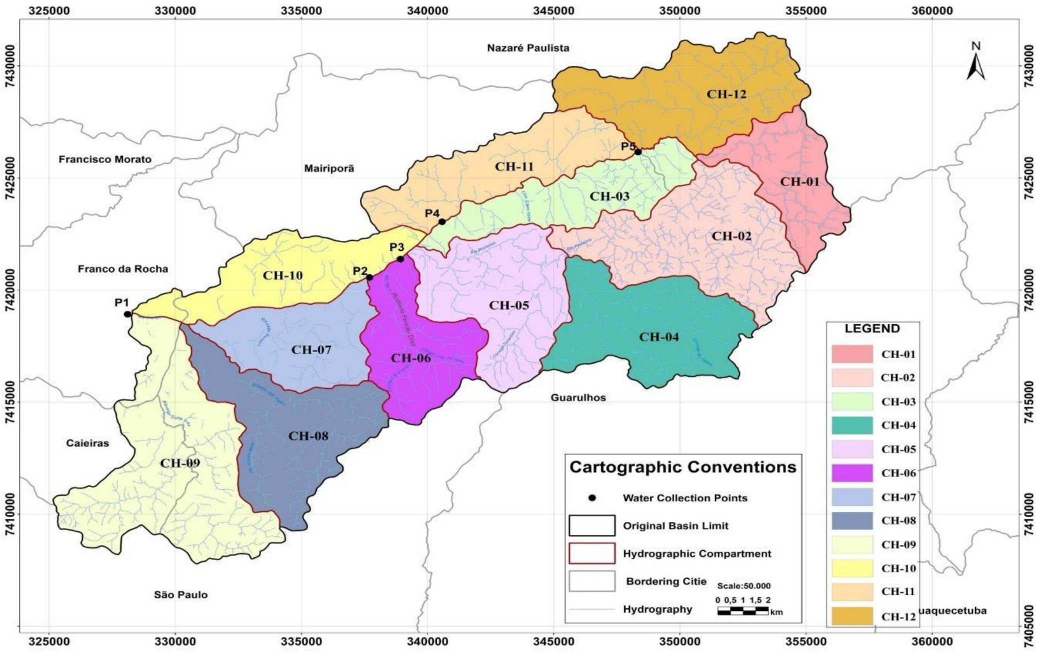

Figure 2. Location of the investigated sections.

At each section, the width, depth, bed topography, current velocity, and discharge were measured. The suspended sediment sampling campaigns were carried out at the defined verticals, using the ADCP RS-5 acoustic profiler for flow measurements and the DH-48 sampler for suspended sediment collection. The ADCP RS-5 is a Doppler-effect acoustic device capable of measuring velocities, depths, and generating real-time bathymetric profiles. Operating at a frequency of 3000 kHz, the RS-5 complies with ISO 24578:2021. The data were processed using RSQ software, with prior compass calibration and exported for analysis in spreadsheets (Figure 3).

Figure 3. ADCP RS-5.

The data sheet generated by the ADCP RS-5 includes key information such as the site, location, measurement date, operator, river width, cross-sectional area, discharge, water depth, current velocity (m/s) of the selected transect, and photographic documentation.

For suspended sediment sampling, the Equal Width Increment (EWI) method was employed using the DH-48 sampler. This method ensures cross-sectional representativeness by collecting samples at a constant velocity during both the descent and ascent along the sampled vertical, following the recommendations of Carvalho (2008), starting from the standard vertical (Figure 4). For bedload sediment collection, Van Veen and Rock-Island type samplers were used (Figure 4). Sampling was conducted across multiple verticals, avoiding stagnant water areas or locations with hydraulic interference, such as behind piers or sandbars.

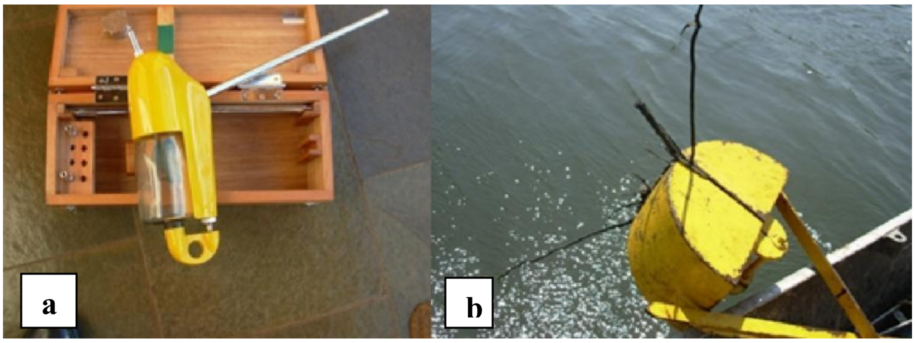

Figure 4. a) DH-48 sampler b) Van Veen sampler.

The field data sheet used for suspended sediment sampling includes details such as the reservoir name, sampling location, UTM coordinates, river width, type of equipment used for collection, depth of the sampled water column, spacing between sampled verticals, standard vertical, sampling time, sample volume collected per vertical, vertical velocity, selected transect, and photographic documentation.

Given the low concentration (< 20 mg/L) of suspended sediments in the investigated stretch, 10 liters of sample (water + suspended sediment) were collected for each section. The samples were sent to the laboratory of the Section of Investigations, Risks and Environmental Management – Sirga, at IPT, where the concentration of suspended sediments by volume (mg/L) was determined using the evaporation method. The values of suspended sediment concentration by volume are used to calculate the solid discharge of suspended sediments.

The method used is described in Procedure CETAE-LRAC-PE-008 – "Concentration of Total Dissolved Solids (TDS) and Suspended Material (SM)," based on the method described in the Sedimentometric Practices Guide (Carvalho *et al.*, 2000).

Grain size was determined by hydrometer sedimentation for fine grains (quantification limit ≈ 0.001 mm) and by wet sieving for sand (lower mesh 0.075 mm); instruments (hydrometers, balances, cylinders, sieves) were calibrated, and a process blank was run for sedimentation. TDS and TSS were measured gravimetrically; quantification limits were 59.28 mg L^{-1} (TDS) and 0.66 mg L^{-1} (TSS), with calibrated glassware/ovens and a deionized-water blank; TDS was analyzed in triplicate (mean reported), while TSS is not routinely replicated. The laboratory participates in periodic proficiency tests, and combined measurement uncertainties are calculated under internal procedure IPT-18091 (available on request).

3. RESULTS AND DISCUSSION

Below are the results obtained regarding the monitoring of suspended solid discharge in the drainage basin of the Paiva Castro Reservoir, containing data on monthly flows (m^3/s), suspended sediment concentration by volume (mg/L), total dissolved solids (mg/L), and suspended solid discharge (t/day) for the period from October 2023 to December 2024.

The liquid discharge (flow rate) was determined from the wetted sections using the ADCP RS-5 equipment. Figure 5 shows the flows recorded at the five sedimentometric sections during the period.

Regarding the flow rate, peaks exceeding 30 m^3/s were observed, associated with precipitation events with accumulations above 100 mm, especially in October and November 2023, and January, March, and December 2024. However, in several months with rainfall totals below 100 mm (such as December 2023 and most of the second half of 2024), high flows were also recorded. This behavior is attributed to the influence of Tunnel 5, which artificially regulates the flow between the Juqueri River and the Atibainha Reservoir, in the municipality of Nazaré Paulista.

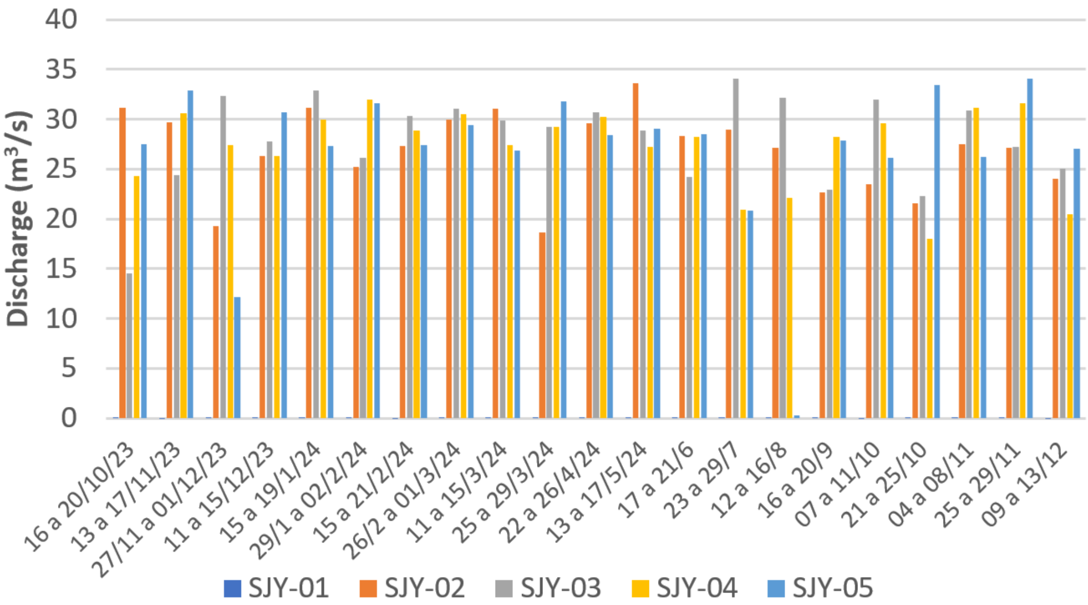

Figure 5. Graph showing the flows recorded at the five sections during the period.

Regarding the concentration, the monthly data (Figure 6) show that suspended sediment concentrations exceeding 30 mg/L occurred when it rained the nights before sampling, as well as in other situations related to construction works at the Sabesp MHP (Micro Hydropower Plant) being built upstream of the sampling sections.

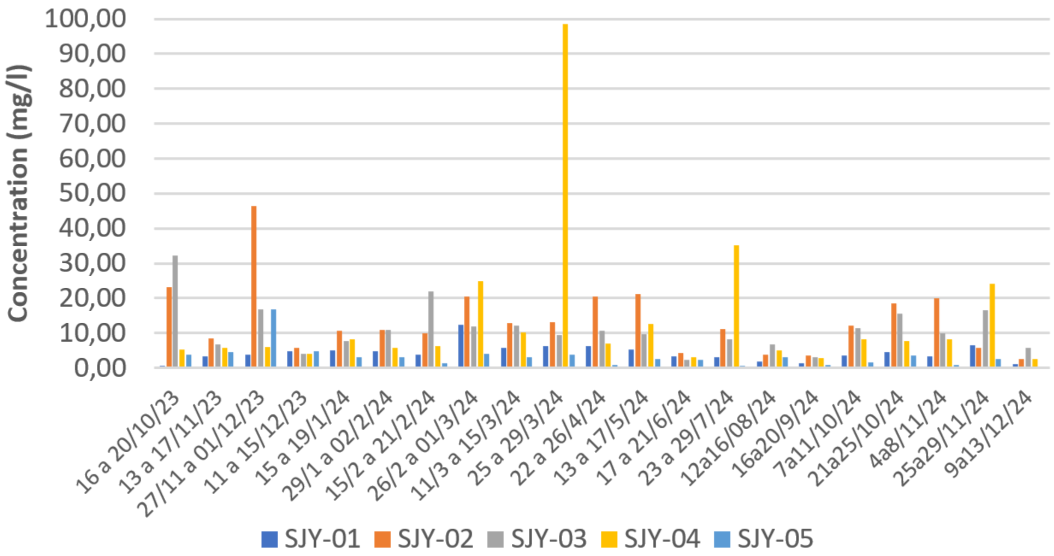

Figure 6. Monthly data of suspended sediment concentrations (mg/L) from the five sections investigated during the period.

Figure 7 illustrates these situations, highlighting the brownish (“muddy”) color of the water, where section SJY-03, on October 17, 2023, recorded 32.25 mg/L due to rainfall the previous night. The same occurred at section SJY-02 on November 27, 2023, which recorded 46.30 mg/L. High concentrations were also recorded at section SJY-04 on March 25, 2024 (98.59 mg/L) and July 23, 2024 (35.07 mg/L) due to construction works (upstream) at the Sabesp MHP (Micro Hydropower Plant).

Figure 7. Highlight of the sections that showed high suspended sediment concentrations.

Regarding the concentration of total dissolved solids (TDS) in watercourses, it can be significantly influenced both by surface runoff, especially in agricultural areas, and by point sources of pollution, such as sewage discharges and industrial effluents. Although not visible, the dissolved load can represent an important portion of the suspended solid discharge. Figure 8 presents the monthly TDS data for the five sections investigated during the period.

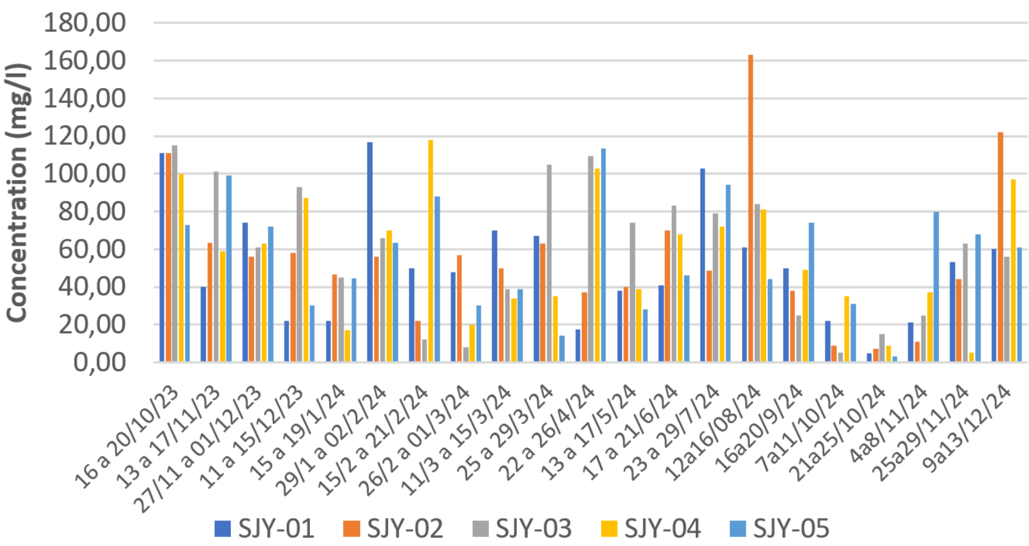

Figure 8. Monthly data of total dissolved solids (mg/L) concentrations from the five sections investigated during the period.

Regarding Figure 8, it can be observed that the highest concentrations are in the range of 100 to 170 mg/L, with emphasis on section SJY-02, which on August 14, 2024, recorded the highest concentration, at 163.00 mg/L.

Regarding the suspended solid discharge (Qss), it usually represents the largest portion of the total solid load in the watercourse, corresponding on average to between 70 and 95% of the total solid load. This proportion depends on the position of the cross-section in the watercourse and other factors (Carvalho *et al.*, 2000).

The calculation of the Suspended Solid Discharge (Qss) value considers that sediments move at the flow velocity throughout the entire cross-section. The concentration corresponds to the average value for the section, and the suspended solid discharge is equal to the product of the liquid discharge (flow rate) and the suspended sediment concentration, both measured at the time of sampling. The suspended solid discharge in t/day (Qss) is determined using Equation 1:

$$Q_{SS} = 0{,}0864 * Q_l * C_s \quad (1)$$

Where: Q_{ss} = suspended solid discharge (t/day); Q_l = liquid discharge (m³/s); C_s = average concentration (mg/L); 0.0864 = unit conversion factor.

Figure 9 presents the monthly suspended solid discharge (t/day) results for the sedimentometric sections defined in the drainage basin of the Paiva Castro Reservoir (SJY-01 to SJY-05), for the period from October 2023 to December 2024.

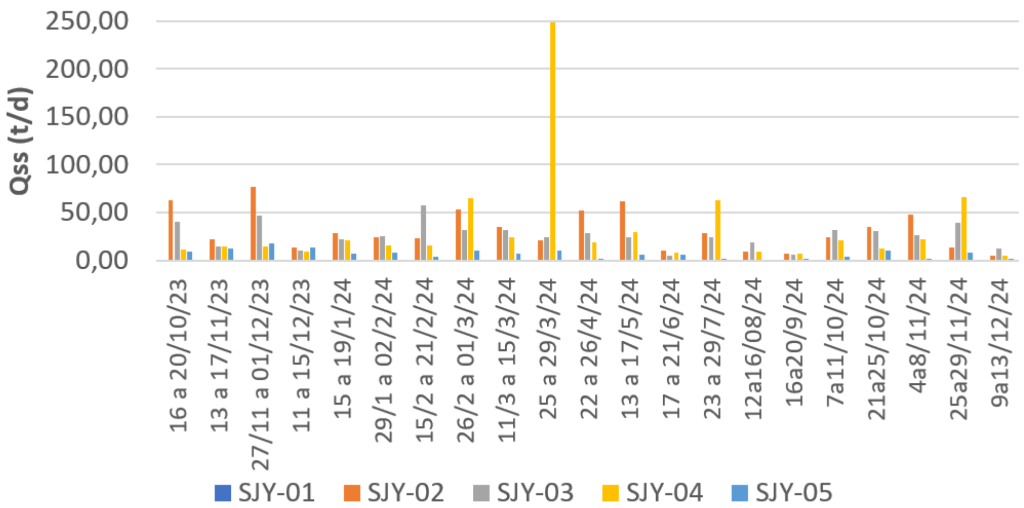

Figure 9. Monthly data of suspended solid discharge (Qss) from the five sections investigated during the period.

As observed in Figure 9, the highest recorded values of suspended solid discharge were due to upstream earthmoving works (construction of the hydroelectric plant, Sabesp MHP), which increased the concentration of suspended sediments. An example is the suspended solid discharge recorded on March 23, 2024, at section SJY-04, which reached 249 t/day, the highest recorded value. Another factor that led to an increase in suspended sediment concentration—and consequently, in suspended solid discharge—was rainfall during the nights preceding sampling, as observed at section SJY-02 on November 29, 2023, which recorded a suspended solid discharge of 77.28 t/day; section SJY-03 on February 15, 2024, which recorded 57.25 t/day; and section SJY-05 on November 28, 2023, which also recorded 57.25 t/day.

It can also be observed in Figure 9 that section SJY-01 did not record significant suspended solid discharge values, since the flows were very low (zero flow) and, in some cases, negative, implying deposition rather than transport of suspended sediments.

Results indicate a seasonal and event-driven pattern: a few stormflows tended to dominate annual suspended-sediment loads, with SSC peaks higher upstream and progressively damped toward the reservoir backwater. Hysteresis between discharge and SSC points to proximal sources mobilized on the rising limb and supply limits as flows recede. Grain-size shifts and nonlinear SSC–Q relations support a transport-to-supply-limited transition through events. Management should prioritize storm-period sampling, refine turbidity–SSC calibrations at high flows, and target erosion control in contributing sub-basins.

4. CONCLUSIONS

Overall, the monitoring indicates event-driven and spatially contrasted sediment dynamics with clear water-quality signals across the basin. Average SSC ranged 3.29–13.89 mg/L, with the highest values often coinciding with prior-night rainfall and ongoing construction at the upstream Sabesp MHP. Peak suspended-solid discharges reached 249 t/day at SJY-04 (23 Mar 2024), 77.28 t/day at SJY-02 (29 Nov 2023), and 57.25 t/day at SJY-03/05, while SJY-01 (downstream of the dam) was near zero due to low and occasionally reverse flows. TDS exceeded SSC in most sections, indicating mixed diffuse and point-source inputs; SJY-02 showed the highest TDS (163 mg/L), with others around 52–60 mg/L.

The overall average suspended solid discharge across the sections was approximately 97.44 t/day, indicating a significant volume of sediment transported by the Juqueri River. However, not all of this sediment reaches the reservoir, as part may be deposited along the river course, especially in backwater areas. This highlights the need to continue studies to assess the reservoir's silting potential and cumulative effects over time.

Therefore, the data obtained provide a basis for integrated basin management, enabling the identification of the most critical sections, understanding the impacts of human activities, and formulating mitigation measures. Continuing the monitoring until December 2025, especially in a scenario with higher rainfall volumes, will be essential to deepen the understanding of flow and sedimentation regimes, thus enabling the development of more effective strategies for water resource conservation and erosion control.

Monitoring should prioritize event-responsive sampling and the deployment of continuous turbidity sensors at SJY-02 and SJY-04 to capture load peaks and reduce uncertainty via site-specific turbidity–SSC ratings. Upstream control should focus on sub-basins contributing to SJY-02 (higher TDS) and SJY-04 (larger Qss peaks), with strengthened BMPs at construction sites and stabilization of eroding channel margins. At the reservoir interface, the resulting metrics should be used to trigger maintenance (e.g., forebay dredging) and to schedule earthworks outside the rainy season, when sediment delivery is typically lower.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

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