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Influence of reservoir cascades on sediment dynamics based on hydrosedimentological modeling: study of the Upper Paraguay river basin – Brazil

Influência da cascata de reservatórios na dinâmica dos sedimentos a partir da modelagem hidrossedimentológica: Estudo da bacia do Alto rio Paraguai - Brasil

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Abstract

Water storage is crucial to optimize water resources, such as power generation, human supply, and flow regulation. Several studies analyze the influence of reservoirs on hydrosedimentological processes, highlighting environmental impacts and changes in the dynamics of watercourses. However, most of these studies focus on individual reservoirs, neglecting the cumulative effects of dams. This research aims to fill this gap by analyzing sediment dynamics in cascade reservoir systems. Five river basins in the Upper Paraguay river region were selected based on the presence of reservoirs, and the SWAT (Soil and Water Assessment Tools) model was used for hydrosedimentological modeling. It was observed that the creation of reservoir cascades significantly impacts sediment dynamics, with emphasis on retention in upstream reservoirs, especially in the largest ones. The location of reservoirs in the basins proved crucial in modifying sediment transport along watercourses. Furthermore, we observed changes in the spatial distribution of sediment production, with inversion of patterns in some cascades. The simulations provided a detailed understanding of sediment behavior, providing important support for managers in making decisions about the installation of new hydroelectric plants, going beyond traditional environmental impact studies.

Keywords:
Sedimentology, Reservoirs in cascades, Reservoir synergy, SWAT model.

Resumo

O armazenamento de água é importante na otimização do uso dos recursos hídricos, como geração de energia, abastecimento humano e regularização de vazão. Diversos estudos analisam a influência dos reservatórios em processos hidrossedimentológicos, destacando impactos ambientais e a alteração na dinâmica dos cursos d'água. Contudo, a maioria desses estudos se concentra em reservatórios individuais, deixando de lado os efeitos cumulativos das barragens. Esse trabalho visa preencher essa lacuna, analisando a dinâmica dos sedimentos em sistemas de reservatórios em cascata. Foram selecionadas cinco bacias hidrográficas na região do Alto rio Paraguai, com base na presença de reservatórios. O modelo SWAT (Soil and Water Assessment Tools) foi utilizado para a simulação hidrossedimentológica. Observou-se que a criação de cascatas de reservatórios impacta significativamente a dinâmica dos sedimentos, com destaque para a retenção nos reservatórios a montante, especialmente nos maiores. A localização dos reservatórios nas bacias mostrou-se fundamental no transporte de sedimentos ao longo dos cursos d'água. Além disso, foram observadas alterações na distribuição espacial da produção de sedimentos, com inversão de padrões em algumas cascatas. As simulações proporcionaram uma compreensão detalhada do comportamento dos sedimentos, oferecendo subsídios importantes para gestores na tomada de decisões sobre a instalação de novas hidrelétricas, indo além dos estudos tradicionais de avaliação de impacto ambiental.

Palavras-chave:
Sedimentologia, Reservatórios em cascatas, Sinergia de reservatórios, SWAT model.

I. INTRODUCTION

The increased construction of hydroelectric plants in Brazil, based on the need for energy for the country's development, has led to the installation of several cascade reservoirs. These reservoirs and land use play a crucial role in sediment dynamics in river basins (Hoffmann, 2017). Understanding sediment dynamics in reservoirs when they are in cascades in the river system and the main influences on the process will contribute to a better management of water resources (Peng; Ji; Gu, 2014).

Cascade reservoir systems can have various definitions, as discussed by several authors. Cardoso-Silva et al. (2017) noted that these systems apply when there are multiple reservoirs in different rivers of the same river basin. Ward e Stanford (1983) characterize a cascade reservoir system as a "serial discontinuity," which can be evaluated through physical parameters (such as temperature), biological phenomena (species abundance patterns) or ecosystem levels (photosynthesis/respiration), with discontinuity measured by the longitudinal distance of a parameter altered by flow regulation. According to Tundisi e Tundisi (2008), a cascade reservoir system consists of multiple hydrologically connected dams, operating in an interrelated manner to achieve common objectives such as water supply and power generation. These authors add that "cascading reservoirs" refer to a sequence of reservoirs in the same watercourse, while a "multiple reservoir system" refers to reservoirs located in different sections of a river, where flows are shared between them.

Sediment load plays an important role in river basin management, especially in combination with precipitation and reservoirs on this phenomenon (Li et al., 2020). Ren et al. (2020) observed that the construction of cascade reservoirs contributed to changes in peak flow propagation time and maximum sediment concentration for some subperiods. Using the rainfall-augmented sediment trapping index (RSTI) linear regression model, the researchers investigated the change in sediment load downstream the reservoir. The Particle Swarm Optimization model combined with the catfish effect algorithm provided an effective approach to obtain the maximum benefits of flow control. An increased siltation loss rate was observed through increased retention time in the flood recession period (Peng; Ji; Gu, 2014). The construction of cascade reservoirs significantly alters the upstream and downstream natural conditions of a river, directly impacting the suspended sediment transport dynamics, especially during extreme events such as floods (Ren et al., 2020; zhang et al., 2022). Sediment load and water flow decreased significantly due to the trapping effects of cascade reservoirs, contributing by 88% and 90%, respectively (Fan et al., 2023). Based on observations of current facilities, as well as the spatial distribution of future facilities, Fantin-Cruz et al. (2020) estimated the impacts of possible new hydroelectric facilities on sediment transport, with more than half of current facilities retaining suspended sediments: 14 of the 29 facilities showed more than 20% net retention of suspended sediments, two others retained between 10 and 20%, seven were within 10%, and six showed more than 10% net release.

The Upper Paraguay river basin, whose water and nutrient flows are conducted to the Pantanal, is important for water resource management to promote the health of ecosystems. This region presents a broad set of critical issues related to the environment, resulting in threats and conflict situations (ANA, 2018). One of these critical issues relates to the increased number of hydroelectric plants, with possibilities in the formation of several reservoir cascades. As of 2018, there were 47 hydroelectric plants in operation and 138 more projects under construction, planned, proposed or identified by the government as prospective locations for the same basin (Fantin-Cruz et al., 2020). The non-governmental organization Ecology and Action (ECOA), based on official data from the National Electric Energy Agency (ANEEL) published an interactive and updated map in 2020 containing, among other information, the distribution of hydroelectric plants in the Upper Paraguay river basin organized by phases, identifying 33 in operation, 13 under construction and 86 under study (ECOA, 2020).

As it is a relatively recent topic, studies on cascade reservoirs have focused predominantly on particular and specific aspects for a basin, such as: optimal storage allocation to increase energy generation, quantification of the effects of future environmental changes that may compromise energy generation, and optimization of the complementary operation of reservoirs (Xie et al., 2024; Zhou et al., 2024; Zhu et al., 2024). They address water quality aspects, such as the influence of cascades on the patterns of distribution and retention of biogenic elements, heavy metals, temperature, nutrients, nitrogen flow and phosphorus flow (Cheniet al., 2024; Li et al., 2024; Sun et al., 2024; Wang et al., 2024; Zhao et al., 2024a, 2024b, 2024c; Zhao; Li; Li, 2024a, 2024b). Other studies address reservoir regulation in snowmelt floods and evaluate changes in river regime for waterways (Liu et al., 2024; Lu et al., 2024). However, these approaches have left an important gap in the literature by neglecting possible influences external to the reservoir environment, such as land use in adjacent river basins, in addition to disregarding more than one basin in the same context.

Therefore, it is essential to model sediments in basins with distinct characteristics, especially those with cascade reservoir systems. This approach enables a more comprehensive analysis of the influences of land use and of the reservoir system itself on sediment dynamics. Thus, the objective of this article was to analyze how reservoir cascade influences sediment dynamics based on the characteristics of the spatial variables of land use, soil and slope and their interactions in several basins within the same ecosystem, with special attention to sensitive areas, such as the Pantanal.

II. MATERIALS AND METHODS

The study area is delimited by the Upper Paraguay river hydrographic region, which includes drainage to the Pantanal (Figure 1). Regions with cascade reservoirs were selected, in addition to some others with isolated reservoirs for comparison. Figure 1 also shows the hydroelectric reservoirs, associated with river basins delimited for the hydrosedimentological simulation.

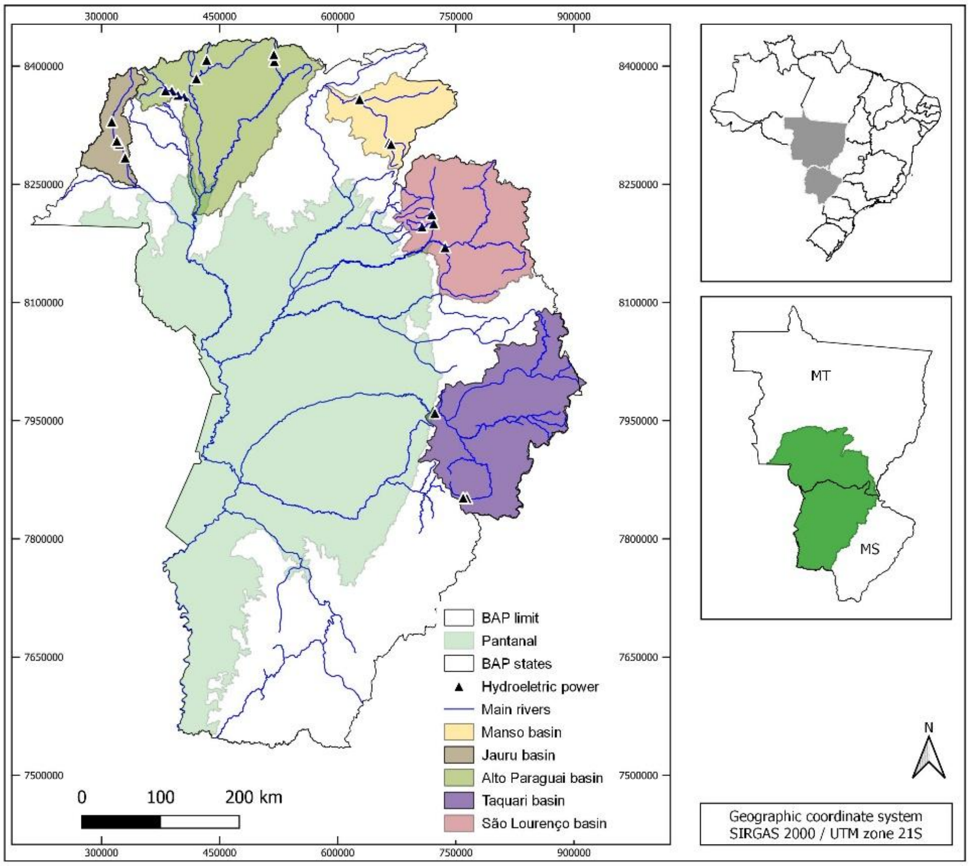

Figure 1 – Study area and single-line diagram of the rivers and hydroelectric reservoirs.

Hydrosedimentological modeling was developed in three main stages. In the first stage, the modeling environment was prepared with the inclusion of land use maps, soil types, digital elevation model and reservoir data (Table 2 – supplementary material), delimiting sub-basins and hydrologic response units (HRUs). In the second stage, climatic data and rainfall and fluviometric station records were included, using the QGis software and the QSWAT plugin. The third step involved the calibration and verification of the parameters of the SWAT model.

Calibration was performed manually, adjusting the parameters until satisfactory performance was achieved. The model was adjusted by comparing the data simulated by SWAT with the observed data, using the Kling-Gupta Efficiency (KGE), Percent bias (PBias) and Pearson's correlation coefficient indices. The calibration and validation periods as well as the number of years used to heat the model varied for each region (Table 1).

Table 1 – Modeling calibration and validation periods.

Basin	Calibration Period	Validation Period	Years of Heating
Jauru	1997-2006	2007-2013	1
Alto Paraguai	1994-2006	2007-2013	2
Manso	2007-2010	2011-2013	1

São Lourenço	2009-2009	2010-2012	1
Taquari	2004-2007	2008-2010	1

Source: Author (2024)

For execution of the SWAT model, it was necessary to enter: Digital Elevation Model (Figure 1 - supplementary material), land use (Figure 2 - supplementary material), and soil types (Figure 3 - supplementary material), and, from them, the software generates the sub-basins and HRUs. HRUs are the basic simulation units in the SWAT model and represent homogeneous areas within the river basin in terms of soils, land use, and slope. The land use classes shown in Figure 2 (supplementary material) are MAPBIOMAS standards (MAPBIOMAS, 2018). The historical series of precipitation, flow and sediment concentration were obtained through the Hidroweb system of the National Water and Basic Sanitation Agency (ANA). The climatic data regarding temperature, solar radiation, relative humidity and wind speed were not sufficient by the bases observed for the periods of historical series of interest of the research. To avoid the process of automatic simulation of these values by the SWAT model, it was decided to use satellite data organized by the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) in the United States, which has a series of 36 years (1979 to 2014). The CFSR was designed and executed as a global high-resolution system coupling atmosphere-ocean-surface land-sea ice system to provide the best estimate of the state of these domains. The distance between the data collection points between latitudes and longitudes is 0.3°. The CFSR website provides daily rainfall, wind, relative humidity and solar data in SWAT model file format for a given location and time period (CFSR, 2021). Figure 4 (supplementary material) represents the distribution of the points of the stations referring to the flow, sediment and precipitation.

The historical series of flow data are monitored daily, unlike sediment data that is collected on average 3 times a year. In this case, it was necessary to fill in the other days by interpolating the correlation between flow and sediment observed. To interpolate the data and fill in the nonexistent days for sediment, the exponential or linear regression method was applied, depending on the best result. The exponential regression applied to the sediment data for interpolation is shown in Figure 6 (supplementary material) with demonstration of the correlation graphs, R^2 and equation of the line.

The hydrological, climatological and reservoir data necessary for the execution of the modeling are described in Charts 1 and 2 and Figure 4 of the supplementary material. The data of the reservoirs were obtained from the National Electric Energy Agency (ANEEL) through a protocol request submitted by the Integrated Ombudsman and Access to Information Platform (FALA.BR) of the Federal Government. The data were submitted in copy of official documents of the companies responsible for the hydroelectric plants, which were organized according to the information necessary for the modeling.

III. RESULTS AND DISCUSSION

The influence of land use on model parameter variability, changes in water flow, and water balance parameters are also identified using a hydrological modeling framework (Sharma; Patel; Sharma, 2022). The hydrosedimentological simulations processed in SWAT presented satisfactory results for the analyses (Tables 2 and 3). The hydrograms and sedimentograms generated from the simulations (Figures 5 and 7 - supplementary material) represent the behavior of the basin data. Figure 2 is the representation of the Upper Paraguay river basin.

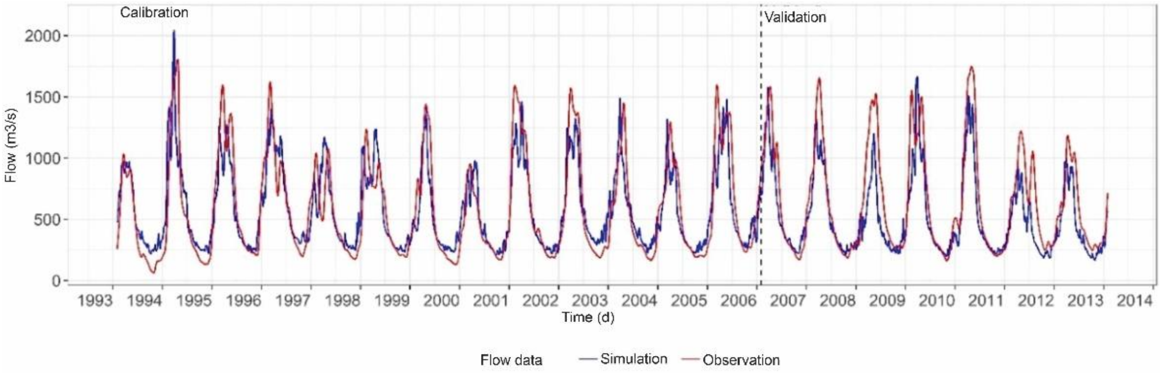

Figure 2 – Flow simulation referring to the modeling of the Upper Paraguay River basin.

The flow simulations of the Jauru river basin show a strong oscillation from the beginning of the simulation until 2003 and then it is smoothed, especially for the flow peaks. This behavior is related to the start of operation of the reservoirs. The flow simulation in the Upper Paraguay river basin shows a general regularity throughout the period, including a good visual adjustment of the hydrograms. In the Manso River basin, flow data show very low values for drought periods. As occurs throughout the period, it can be considered as a normal behavior of the basin. This behavior was also observed by the simulation in the Cuiabá river basin, which includes the Manso river basin (Baldissera, 2005). No special characteristics were identified in the behavior of flow data for the São Lourenço river basin, which showed the typical variations of floods and droughts. However, this basin was one of the most difficult to calibrate. With the Taquari river basin, although the simulated hydrogram follows the observed hydrogram, there is an important difference in the drought period. The values were smoother, with fewer oscillations between peaks and recessions than the values of the flood period. The results of the flow simulations indicate a generally satisfactory performance of the hydrological model, with efficiencies ranging from 0.51 to 0.69 during the calibration and validation periods (Table 3).

Table 2 – Results of the flow simulations.

	Calibration				Validation			
Basins	Period	KGE	pBias	Pearson	Period	KGE	pBias	Pearson
Jauru	1997-2006	0.66	0.03	0.69	2007-2013	0.55	0.13	0.63
Alto Paraguai	1994-2006	0.69	0.08	0.71	2007-2013	0.62	0.12	0.68
Manso	2007-2010	0.65	0.02	0.70	2011-2013	0.61	0.11	0.70
São Lourenço	2006-2009	0.57	0.14	0.75	2010-2012	0.52	0.16	0.69
Taquari	2004-2007	0.55	0.19	0.59	2008-2010	0.51	0.17	0.57

Source: Author (2024).

There is a trend of small reduction in efficiency during the validation periods compared to the calibration periods in all basins, which suggests a generalization capacity of the hydrological model. The pBias values indicate a small positive bias in the simulations, with an average ranging from 0.02 to 0.19, indicating that the estimates tend to be slightly overestimated. As for Pearson's correlation coefficient, the values range between 0.57 and 0.75, indicating a good linear relationship between the simulated and observed data. These results indicate that the hydrological model can adequately reproduce the flow evolutions in the different basins, if considering the application in less restrictive projects. The results presented by the hydrograms for the Upper Paraguay, Cuiabá and São Lourenço river basins are similar to the models calibrated by the MGB software (IPH, 2021) and presented in the project for the implementation of integrated river basin management practices for the Pantanal (Allasia et al., 2015).

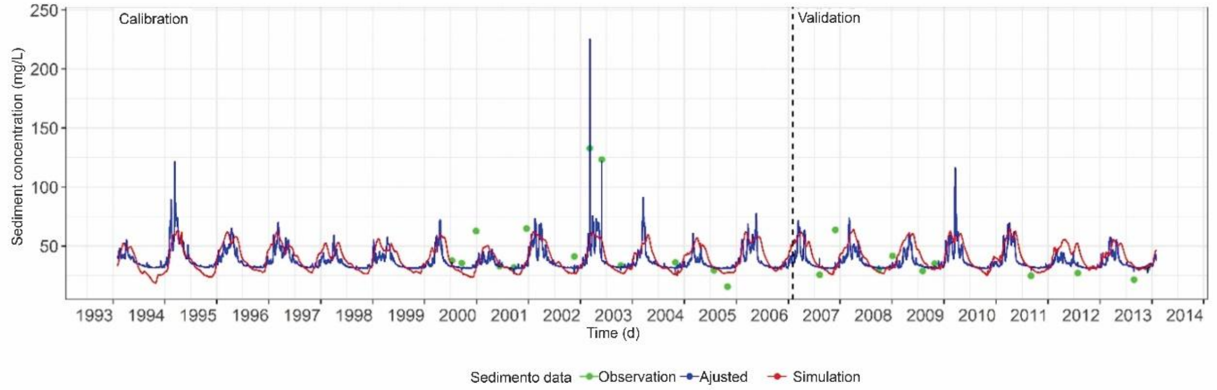

Figure 3 – Sediment simulation referring to the modeling of the Upper Paraguay River Basin.

In the analysis of the sediment concentration simulation, it was observed that all simulated values of the basins were lower than the adjusted values. The simulated data in the drought periods show values with reduced variation. The Upper Paraguay river basin resulted in peak sediment concentration values that are possible outliers. Another point that should be noted as to this basin is the values simulated in the drought periods, which are always below the adjusted values. With a certain similarity to the Jauru river basin, the values simulated in the drought periods for the Manso river basin show reduced variation. For the values in flood periods, the variations of the simulated data follow the observed values, despite being lower in a large part of the period. The variations of the simulated data in the São Lourenço river basin throughout the period and without distinction between floods and droughts follow the adjusted data, but with amplitudes of the simulated data always smaller than the amplitudes of the adjusted data. In the Taquari river basin, the adjusted and simulated data have regular behavior despite the variation of the data in the simulation being smaller than the variation in the adjusted data. That is, the oscillations of the peaks are less intense in the simulation. Importantly, adjusted data for flow are collected daily, while sediment concentration data are interpolated, as described in the methodology, based on samples taken an average of 3 to 4 times a year. This difference in sampling frequency can largely explain any discrepancies in the simulations of sediment concentrations and at the same time the difficulty in calibrations. Table 5 shows the results of the performance of the models through applied indices.

Table 3 – Results of the sediment concentration simulations.

Basin	Calibration				Validation				KGE between observed and
	Period	KGE	pBias	Pearson	Period	KGE	pBias	Pearson	
Jauru	1997-2006	0.61	0.14	0.67	2007-2013	0.55	0.13	0.62	
Alto Paraguai	1994-2006	0.63	0.06	0.70	2007-2013	0.59	0.10	0.63	0.71
Manso	2007-2010	0.59	-0.06	0.65	2011-2013	0.58	-0.12	0.62	0.82
São Lourenço	2006-2009	0.40	-0.04	0.64	2010-2012	0.39	-0.11	0.61	0.47
Taquari	2004-2007	0.58	-0.10	0.62	2008-2010	0.54	-0.12	0.60	0.42

Source: Author (2024).

The results of the simulations for sediment concentrations show a variation in the efficiency of the sedimentological model, with values ranging between 0.40 and 0.63 during the calibration and validation periods. In general, there is a trend of lower performance compared to the results for flow, which is expected and understandable, especially due to the scarcity of observed data, as discussed above. During the calibration periods, the efficiency values for sediment indicated a reasonable ability of the model to reproduce the observed variations. However, during the validation periods, the efficiency decreases slightly, ranging between 0.39 and 0.59, which suggests a reduced ability of the model to predict sediment production and transport patterns. The pBias values indicate a negative bias in the simulations, with an average ranging from -0.12 to 0.14, indicating a trend of underestimation in sediment estimates. As for Pearson's correlation coefficient, the values range between 0.61 and 0.70, indicating a moderate to strong relationship between the simulated and observed data.

The efficiency of the model was also evaluated based exclusively on observed sediment data, as most of the data was adjusted by regression. Despite the significant difference in the amount of observed data in relation to the adjusted data, the models presented a good fit. The values presented in the last column of Table 5 demonstrate this performance, where it can also be observed that only in the Taquari river basin the performance of the observed data series was lower than that of the adjusted series.

In the Upper Paraguay river basin, there is a balance in the distribution of the observed values when compared to the simulated values. About 60% of the simulated values are slightly lower than the observed values. With an even more balanced distribution between the observed and simulated values in the Manso river basin compared to the Alto Paraguay river basin, the simulated values are 50% above the observed values. With the same analyses previously mentioned, the São Lourenço river and Taquari river basins had 71% and 100% of the simulated values below the observed values, respectively. This discrepancy can be interpreted by the lower

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performance of the model in relation to the observed and simulated data presented in Table 5. These results highlight the importance of investing in sediment monitoring, enabling an increase in measurements so historical series have more relevance in the models and provide better simulations.

The sediment production rate generated by the simulations were spatialized as a function of HRUs. These values were obtained from the output.std file of each basin and treated for adaptation of the structure. This adaptation was for the application in the R software responsible for most of the processes of analysis of the results. After data treatment, sediment production rate values were included in the shape file for spatialization (Figure 4).

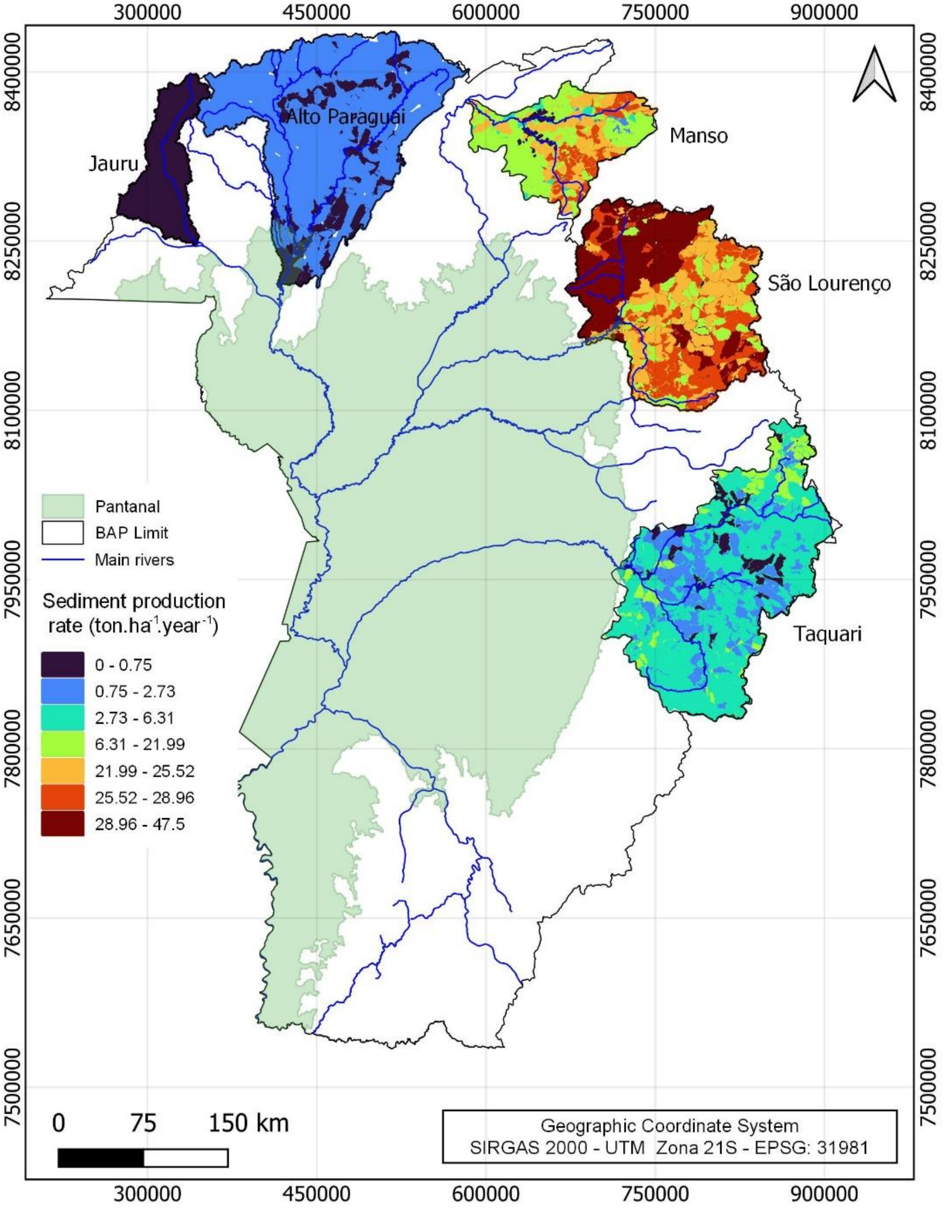

Figure 4 – Sediment production rate of the basins modeled for the Upper Paraguay river basin region.

When examining land use in all basins (Table 3 – supplementary material), it was observed that the highest sediment production rates occur in basins with greater extension of agricultural areas, reaching 7%, 8% and 16% for the Manso, Taquari and São Lourenço basins, respectively. Although agricultural areas represent a small fraction of the landscape in relative terms, this observation highlights their influence on the sedimentological process. The highest soil erosion rate was observed in cultivated land, which increased from 40.86 ton.ha^{-1}.year^{-1} in 2000 to 53.9 ton.ha^{-1}.year^{-1} in 2020. This is related to the expansion of agricultural lands (Anley; Minale, 2024). Importantly, this finding does not imply that agriculture is primarily responsible for sediment production in the basin, but rather that it is a highly sensitive variable. Cultivated land is naturally susceptible to the generation of runoff, which in turn increases sediment production and transport, especially as they are not covered in part of the area (Kenea et al., 2021). The other land uses are essentially divided between pasture and natural vegetation. Pasture ranges from 33% to 58% between basins, while natural vegetation ranges from 34% to 57%. (Chart 3C – supplementary material).

The sediment production rate ranged from 0.21 to 47.5 ton.ha^{-1}.year^{-1}, in all basins. However, there was a strong difference between them, especially between Jauru and Alto Paraguay and the others, Manso, São Lourenço and Taquari. The 7-range classification for sediment production rate shown in Figure 4 was prepared to show the Jauru river basin, which presented values well below the others. This difference is evident when observing the ranges of the rates of each basin (Figure 5).

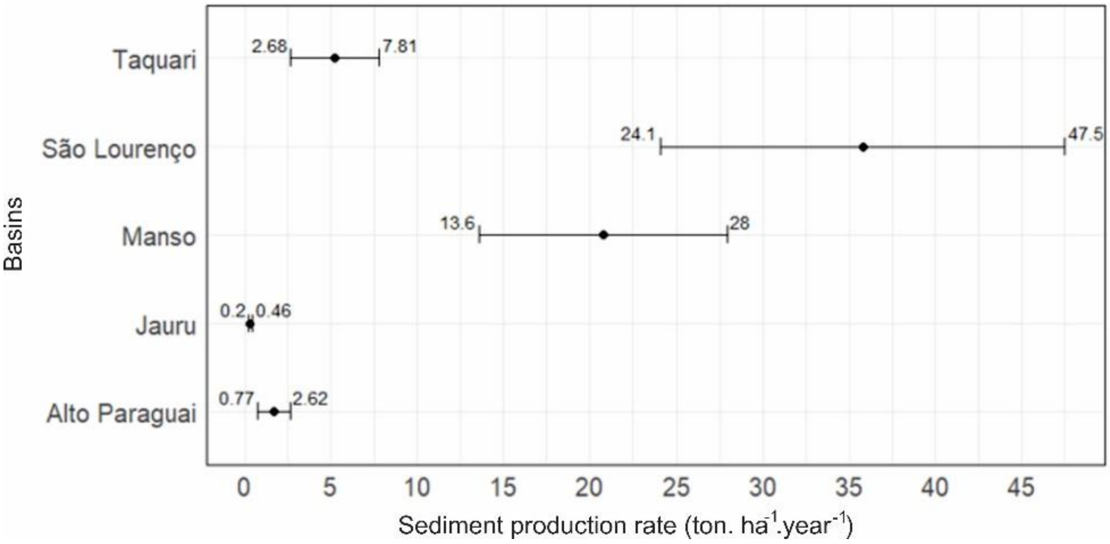

Figure 5 – Range for sediment production rates in each basin.

The ranges observed for sediment production rates show significant diversity, indicating that the amplitude of these values is not necessarily related to the area of the basins. This phenomenon is clearly illustrated by the Upper Paraguay basin, which, despite being the largest in territorial extension compared to the others, has the second lowest amplitude of sediment production rate. In addition, when considering the range of sediment production rates in all simulated basins, there is an extremely marked difference when comparing the maximum values of the basins with the lowest rate observed. The Jauru basin's highest rate was 0.46 ton.ha^{-1}.year^{-1}, while the highest rates of the other basins are significantly higher: the Upper Paraguay basin reaches a rate of 2.62 ton.ha^{-1}.year^{-1}, representing a difference of 5.7 times in relation to the Jauru rate. The Taquari basin has a rate 16.9 times higher, the Manso basin rate is 60 times higher, and the São Lourenço basin has a rate 103 times higher, always compared to the highest rate of the Jauru basin. These values indicate the need for a detailed analysis in each basin to understand the factors that influence these disparities in sediment production rates.

Sediment production accumulated in the outlet of the reservoirs

Reservoirs are expected to play the role of retaining the sediments produced in their drainage areas over time, as a function of the production rate, as observed by Fan et al. (2023). To understand this dynamics, cumulative graphs for sediment in the outlet of the reservoirs were prepared, enabling the analysis of the behavior of the curves. Because the data are cumulative, the lines are expected to be increasing over time.

Five basins were simulated in the study, each with their respective reservoirs. A specific graph was prepared for each basin: Jauru river basin, with 5 reservoirs (Figure 6A); Upper Paraguay basin, with 7 reservoirs, being cascade 1 (Figure 6B) and cascade 2 (Figure 6C); Manso river basin, with 3 reservoirs (Figure 6D); São Lourenço river basin, with 5 reservoirs (Figure 6E); Taquari river basin, with 3 reservoirs (Figure 6F).

These graphs enable us to visualize and analyze the behavior of sediments accumulated at the outlet of the reservoirs over time, demonstrating changes in the natural conditions downstream the river, as also observed by Ren et al. (2020) and Zhang et al. (2022).

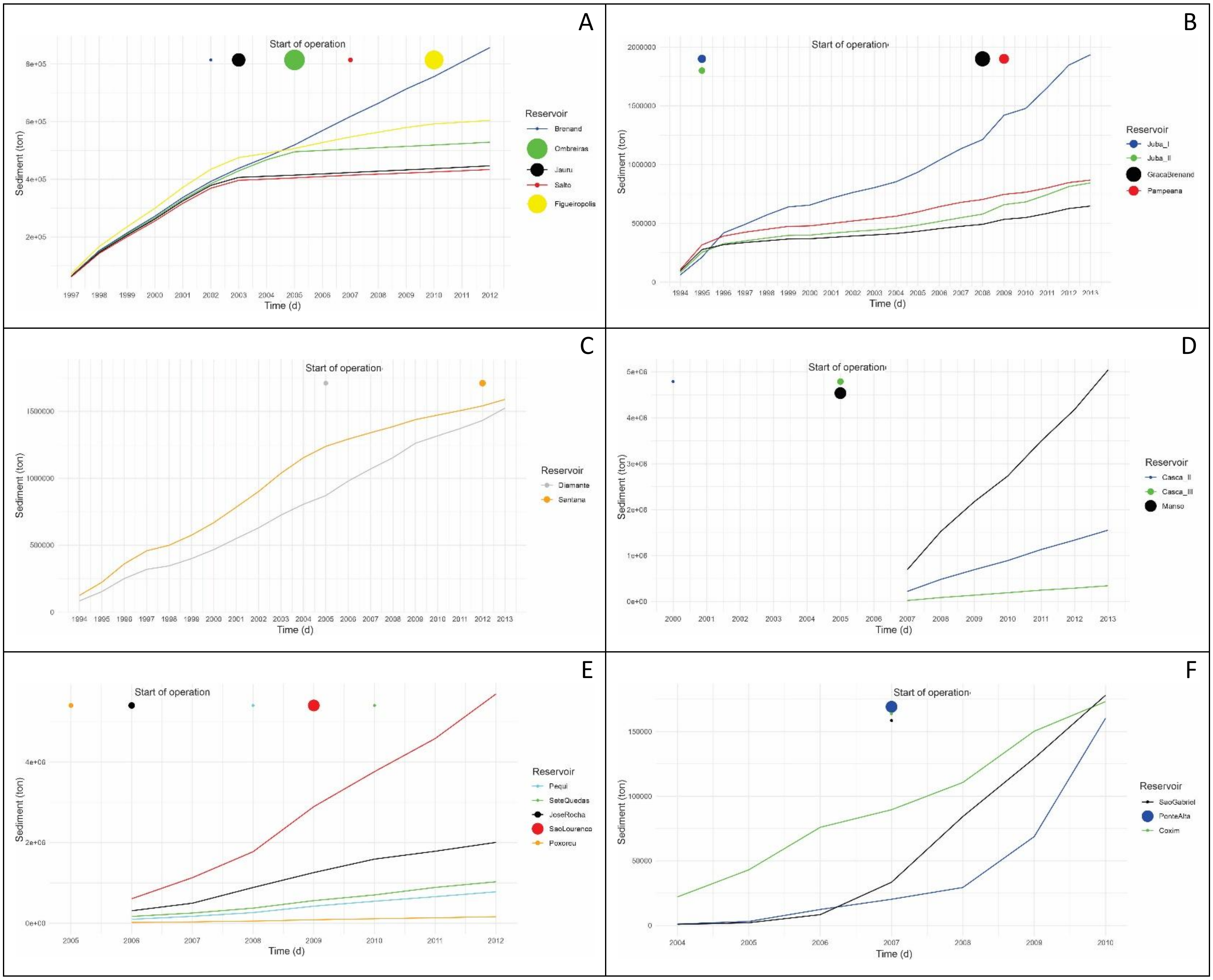

Figure 6 – Sediment production accumulated at reservoir outlets - A) Jauru River Basin – B) Upper Paraguay Basin - Cascade 1 – C) Upper Paraguay Basin - Cascade 2 – D) Manso River Basin – E) São Lourenço River Basin – F) Taquari River Basin.

The first important observation about the basins and their reservoirs was the formation of cascades. In the Jauru river basin, all reservoirs form a single cascade (Figure 6A). In the Upper Paraguay basin, there are two cascades: the first is composed of the Jubá I, Jubá II, Graça Brenand and Pampeana reservoirs, in that order from upstream to downstream (Figure 6B); the second cascade is formed by the Diamante and Santana reservoirs, also in that order from upstream to downstream (Figure 6C). The Manso River basin, with three reservoirs, presents one cascade considering only the Casca II and Casca III reservoirs (Figure 6D). In the São Lourenço river basin, there is no cascade formation, as the reservoirs are distributed throughout the basin, without significant mutual influences (Figure 6E). Finally, the Taquari River basin has one cascade formed by the São Gabriel and Ponte Alta reservoirs (Figure 6F).

The Brenand, Ombreiras, Jauru, Salto and Figueirópolis reservoirs (in the Jauru River basin), as well as the Jubá I and Jubá II reservoirs (in the Upper Paraguay basin), showed a typical behavior of influence on sediment dynamics. There is a reduced sediment production downstream each reservoir after the year of start of operation, which indicates the effective retention of sediments by these reservoirs. Although the line for accumulated sediment of the Brenand reservoir shows no significant change, there is a small change in the year of start of operation. This small difference is justified by the size of the reservoir. It was not possible to make inferences about the influence of reservoirs in the Manso River basin, as the modeling data are for periods after the start of operation of these reservoirs. In addition, the reservoirs of the basins of the São Lourenço river, and the Taquari, Pampeana, Graça Brenand, Santana and Diamante rivers (Upper Paraguay basin), showed no significant influence on sediment dynamics as a function of the start of operation.

The analysis of sediment dynamics as a function of the geospatial positions of cascade reservoirs shows important elements. Although there is no significant change in the curve for sediment accumulated in the Brenand reservoir, a slight reduction between 2002 and 2003 suggests sediment retention, which influences the Jauru and Salto reservoirs, located downstream. The Brenand reservoir, with only 4.5 hectares of area and 42 hm³ of volume, explains this behavior. The Jauru reservoir, with 380 hectares and 250 hm³, retains sediments that affect the Salto and Figueirópolis reservoirs. The Salto reservoir responds similarly to the Jauru reservoir, as indicated by the parallel curves for accumulated sediments. This pattern is justified by the spatial proximity of the Salto reservoir just next to Jauru reservoir. Similarly, the Jubá I and Jubá II reservoirs directly influence those downstream, while the Graça Brenand and Pampeana reservoirs do not change sediment dynamics soon after the start of operations.

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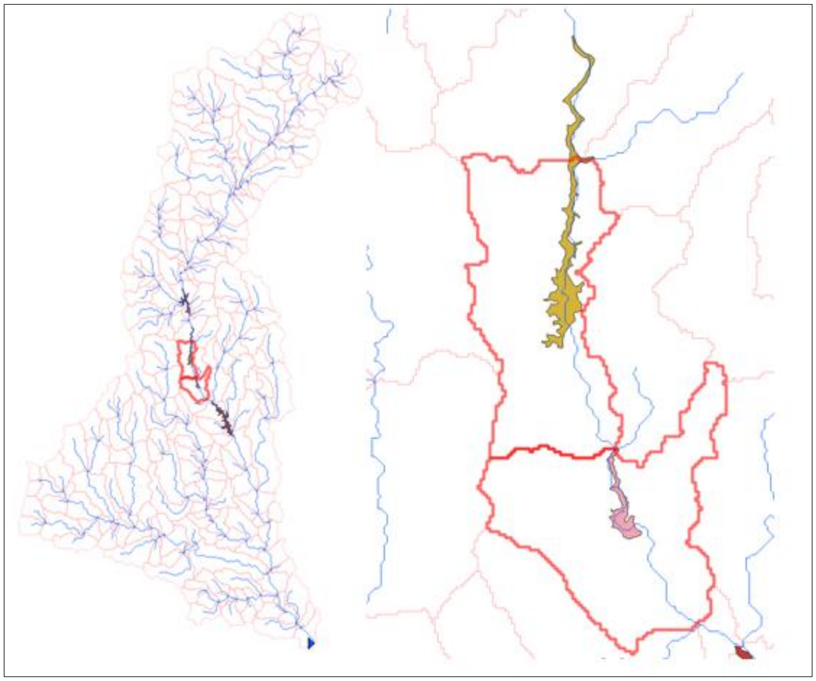
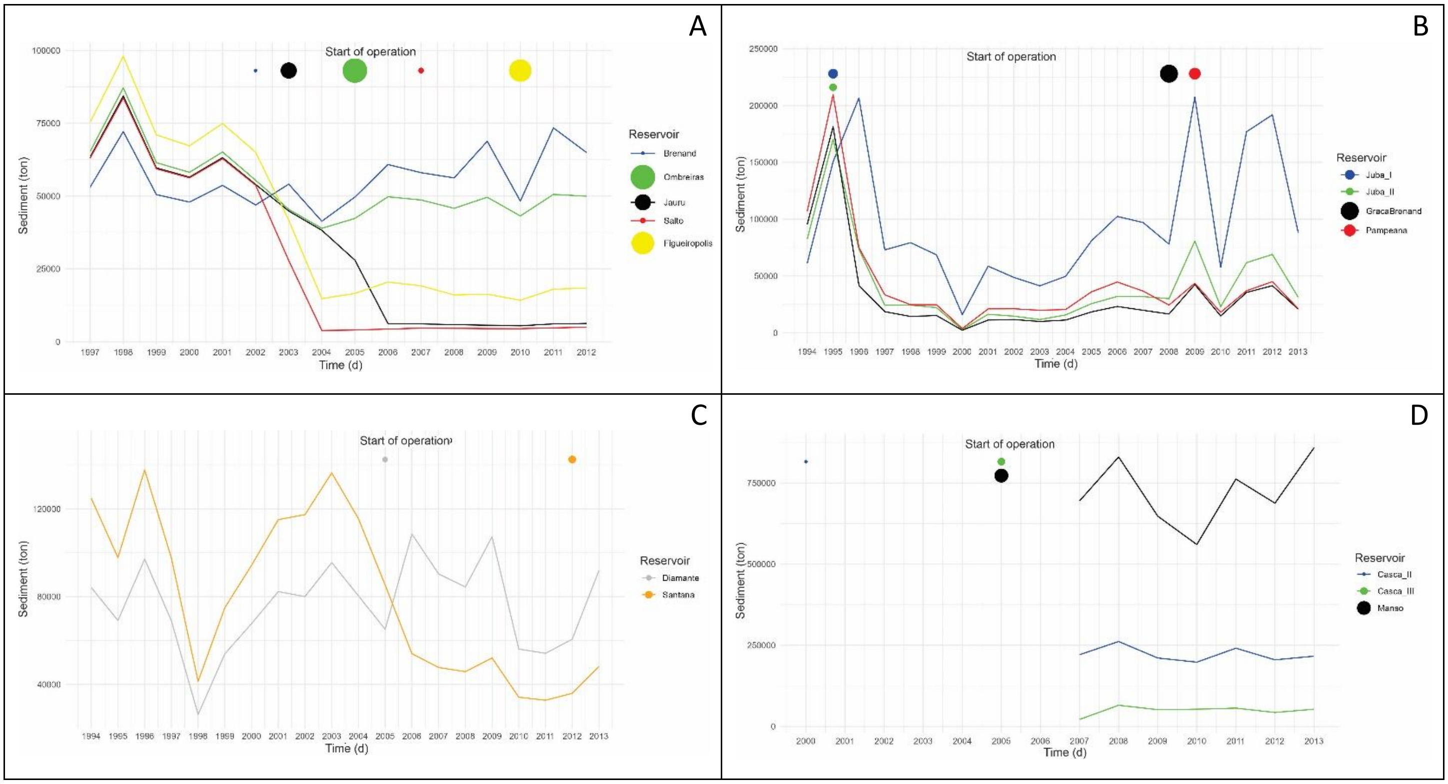


Figure 7 – Jauru River Basin with emphasis on the Jauru and Salto reservoirs.

Sediment production in the outlet of the reservoirs

This topic presents the sediment dynamics in each reservoir of the simulated basins, considering the non-accumulated production in the outlets of the reservoirs for new observations.



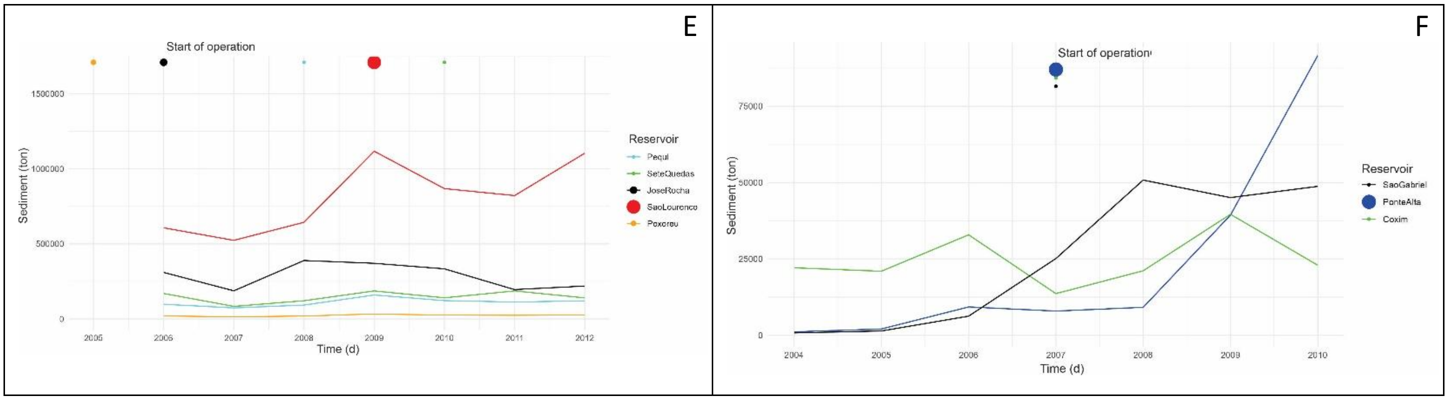


Figure 8 – Non-accumulated sediment Production - A) Jauru River Basin – B) Upper Paraguay Basin – Cascade 1 - C) Upper Paraguay River Basin - Cascade 2 – D) Manso River Basin - E) São Lourenço River Basin – F) Taquari River Basin.

It is observed that all reservoirs upstream a cascade showed higher sediment production, even with a smaller drainage area, which proves sediment retention.

The Ombreiras reservoir (Figure 8A) presented important sediment retention, which after the year of start of operation causes the downstream reservoirs to have a significant reduction in sediment production.

Also important is Cascade 2 of the Upper Paraguay basin (Figure 8C). Before the installation of the Diamante and Santana reservoirs, sediment production in the sub-basins was proportional to the drainage area. However, after the installation of the Diamante reservoir, this behavior was reversed, clearly demonstrating sediment retention. Even though it is a small reservoir, with 49 hectares of area and 75 hm^3 of volume (Table 2C – supplementary material), the Diamante reservoir proved able to retain sediments.

The cascade in the Manso River basin formed by the Casca II and Casca III reservoirs (Figure 8D) also demonstrates a good sediment retention capacity. The sub-basin further downstream the Casca II reservoir should have higher sediment productivity because it has a larger drainage area. However, the Casca III reservoir with 32 hectares of area and 124 hm^3 of volume can retain much of the sediments

Other isolated observations may be made. In the São Lourenço river basin (Figure 8E), which does not have a reservoir cascade formation, sediment dynamics directly follows the relationship with the drainage area. The highest sediment productions refer to the largest drainage areas. It was necessary to apply a different scale of values to observe the sediment behavior in the Poxoréu reservoir, which has a very small drainage area and, consequently, a low sediment production.

These analyses show the importance of the reservoirs' configuration and location in sediment retention and in modifying the dynamics along the watercourses, which may contribute to the management of the reservoirs as suggested by LI et al. (2020).

IV. CONCLUSIONS

Reservoir cascade formation was a significant phenomenon observed in several basins, where sediment retention was evident in upstream reservoirs. This was particularly important in the larger reservoirs, which demonstrated an effective sediment retention capacity, directly influencing the downstream reservoirs. The analysis of non-accumulated sediment production in reservoir outlets confirmed this trend, showing greater sediment production in sub-basins upstream the cascades, followed by a significant reduction in sub-basins downstream.

The reservoirs' configuration and location were found to be crucial factors in modifying sediment dynamics along watercourses. The reservoirs not only retained sediments, but also altered the spatial distribution of sediment production, as shown by the reversal of patterns observed in some cascades. These results underscored the importance of considering the effects of reservoirs in the management and conservation of water resources, especially in areas where erosion and sediment transport have posed significant challenges to water quality and the health of aquatic ecosystems.

The results of the simulations and all the analyses of the results of this research provided a detailed understanding of sediment behavior in different areas, highlighting the influence of reservoir cascades. Despite the complex interactions of the elements in the hydrosedimentological modeling, associated with the diverse landscape, substantial findings were obtained. Such findings inform public managers on the importance of in-depth studies to support decision-making in the process of licensing the installation of new hydroelectric plants, going beyond traditional environmental impact studies.

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