RBRH
Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 29, e16, 2024
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.292420230138

Determination of suspended sediment rating curve and models to estimate the suspended solids concentration in the Pandeiros river, Brazil

Determinação das curvas chave de descarga sólida em suspensão e de modelos para estimativa da concentração de sólidos suspensos no rio Pandeiros, Brasil

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Received: November 30, 2023 - Revised: January 24, 2024 - Accepted: April 20, 2024

ABSTRACT

The present study aimed to fit the sediment rating curves in three sampling points of the Pandeiros River (Brazil), as well as to establish models for estimating the suspended solids concentration using the flow and turbidity data. The study used data measured between May 2019 and January 2023. The following variables were determined: flow, suspended solids concentration, suspended solids discharge and turbidity. The sediment rating curves were fitted using the power model. The coefficient of determination was higher than 0.93 for all the fits. As for the models fitted to estimate the suspended solids concentration, the best results were obtained by the power model, using flow as the independent variable, and the linear model, using turbidity as the independent variable. It was concluded that both the rating sediment curve and the models fitted to estimate the solids concentration can be used to assist in the hydrosedimentological monitoring of the Pandeiros River.

Keywords: Water resources; Sediments; Hydrosedimentology; Pandeiros river; Sediment rating curve.

RESUMO

O presente estudo teve como objetivo ajustar as curvas chave de transporte de sedimentos em três seções do rio Pandeiros (Brasil), bem como estabelecer modelos para a estimativa da concentração de sólidos suspensos utilizando as variáveis vazão e turbidez. O estudo utilizou dados medidos entre maio de 2019 e janeiro de 2023. Foram determinadas: a vazão, a concentração de sólidos suspensos, a descarga sólida em suspensão e a turbidez. As curvas chave de sedimentos foram ajustadas seguindo o modelo potencial. O coeficiente de determinação foi superior a 0,93 em todos ajustes. Quanto aos modelos ajustados para estimar a concentração de sólidos suspensos, os melhores resultados foram obtidos pelo modelo potencial, utilizando a vazão como variável independente, e linear, utilizando a turbidez como variável independente. Concluiu-se que as curvas chave de sedimentos e os modelos ajustados para estimar a concentração de sólidos podem ser utilizados para auxiliar no monitoramento hidrossedimentológico no rio Pandeiros.

Palavras-chave: Recursos hídricos; Sedimentos; Hidrossedimentologia; Rio Pandeiros; Curva chave de sedimentos.

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INTRODUCTION

The activities carried out in a watershed can directly affect the watercourse, influencing water quality and hydrosedimentological processes (Giri & Qiu, 2016; Mello et al., 2020; Su et al., 2016). Monitoring solid discharge can reveal the impact of anthropogenic interference in the basin (Garrido et al., 2018; Louzada et al., 2022; Melo et al., 2020; Silva et al., 2021) and assist in the decision-making process aimed at conservation and rational use of water resources.

The Pandeiros River basin, considered an Environmental Protection Area, is located in the Minas Gerais state, Brazil (Instituto Estadual de Florestas, 2013a; Minas Gerais, 1995), and erosion processes are recurrent in its drainage area, with a significant number of gullies (Companhia de Desenvolvimento dos Vales do São Francisco e Parnaíba, 2021; Lima et al., 2019) which can significantly affect sediment transport in the Pandeiros River. Furthermore, the Pandeiros River State Wildlife Refuge (Minas Gerais, 2004a) is located in the lower course of the Pandeiros River, which is an integral protection conservation unit (Instituto Estadual de Florestas, 2013b) designed to protect natural environments that provide conditions for the existence or reproduction of species or communities of local flora and resident or migratory fauna (Brasil, 2000).

The information obtained from the hydrosedimentological monitoring of the Pandeiros River is of great importance, as it can be used by the authorities responsible for the management of the conservation units located in the Pandeiros River basin. Additionally, this information can aid in the decommissioning of the Pandeiros Small Hydroelectric Plant, which ceased energy production in 2008.

However, measuring solid discharge is a laborious process, which requires financial resources and cannot always be carried out very often, since it involves traveling to the field to determine the flow rate and collecting water samples to determine the suspended solids concentration (Bright et al., 2020; Melo et al., 2020; Menezes et al., 2021; Sultana, 2020). In addition, the direct sampling is a challenging task under high-flow conditions (Aleixo et al., 2020), when most of the sediment is transported (Carvalho, 2008; Hoffmann et al., 2020; Horowitz et al., 2015; Syvitski et al., 2000). Determining the suspended solids concentration is a simple analysis, however, it requires a large amount of time and is considerably more expensive than other alternative methods, such as determining turbidity (Bilotta & Brazier, 2008; Davies-Colley & Smith, 2001).

Turbidity is the degree of attenuation of the intensity that a beam of light suffers when passing through water due to the presence of suspended solids (Companhia Ambiental do Estado de São Paulo, 2018; Putri & Arisalwadi, 2023), and has been used to estimate the suspended solids concentration by several authors (Bilotta & Brazier, 2008; López et al., 2021; Stutter et al., 2017; Villa et al., 2019). Like turbidity, flow can also be used to estimate sediment load by fitting a curve that relates flow to solid discharge or sediment concentration (Carvalho, 2008). Suspended sediment rating curves are used all around the world and are low-cost, reliable (Jung et al., 2020) and can be used in situations where collecting daily information is not economically viable (Melo et al., 2020; Menezes et al., 2021).

Therefore, the aims of this study were: i) to carry out hydrosedimentological monitoring in three cross-sections of the Pandeiros River and provide a general description of sediment transport; ii) to determine the suspended sediment rating curves in the monitored sampling points; and iii) to fit models to estimate the suspended solids concentration using the variables flow and turbidity.

MATERIAL AND METHODS

Study area

The study was carried out in the Pandeiros River basin (3938 km^2), located in the northwest of the Minas Gerais state, Brazil (Figure 1). The Pandeiros River is a tributary on the left bank of the São Francisco River and is considered a permanent preservation river by Law Nº 15 082, of April 27, 2004 (Minas Gerais, 2004b).

The Pandeiros River basin is considered an environmental protection area by State Law Nº 11 901 of September 1, 1995,

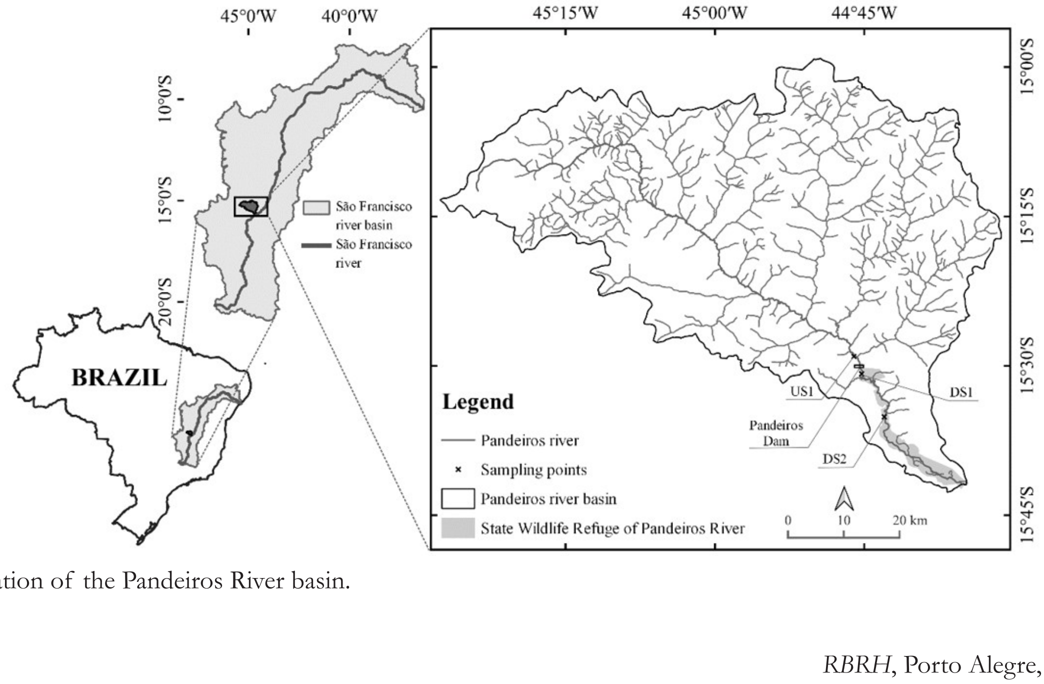

Figure 1. Location of the Pandeiros River basin.

known as the Pandeiros River Environmental Protection Area (APA Pandeiros, for its acronym in Portuguese). Also located within the basin is the State Wildlife Refuge of Pandeiros River, created by Decree Nº 43 910 of November 5, 2004, with an area of 61.02 km^2.

The climate in the region is classified as Aw according to the Koppen classification (tropical with dry winter and humid summer) (Martins et al., 2018). The rainy season occurs between October and March, and the mean rainfall for the hydrological year (October to September) is 1085 mm (Junqueira et al., 2020).

The relief classes observed in the study area, considering the classes proposed by Empresa Brasileira de Pesquisa Agropecuária (1979), are: slightly undulating (3-8%, 63.4% of the area); flat (0-3%, 17.2% of the area); undulating (8-20%, 17.1% of the area); strong undulating (20-45%, 2.1% of the area) and mountainous (45-75%, 0.2% of the area). Elevation in the basin ranges from 844 m at the highest point in the basin to 435 m at the mouth of the Pandeiros River.

According to Oliveira (2013), in the Pandeiros Environmental Protection Area, the soil classes of Oxisols and Quartz Entisol stand out, developed from sandstones from the Urucuia formation. According to the Soil Map of the Minas Gerais state (Universidade Federal de Viçosa, 2010), six soil classes are found in the basin, these being: Red-Yellow Oxisol (87.6%); Fluvic Entisol (5.4%); Quartz Entisol (3.2%); Melanic Entisol (3.0%) and Haplic Inceptisol (0.7%) and Litolic Entisol (0.1%).

The land cover is predominantly composed of savannah formations (Savanna Formation - 70.3% and Grassland - 19.3%), which total 89.6% of the area. The other classes observed in the area are Pasture (3.9%), Agriculture and Pasture (2.8%) and Forest Formation (2.0%). Other classes occupy 1.7% of the area. The characterization of land cover was obtained from the Land Use and Cover Map for the year 2020 made available by the MapBiomas project (MapBiomas Project, 2020).

Hydrological monitoring

Monitoring was carried out between May 2019 and January 2023. Due to logistical difficulties, mainly caused by the COVID-19 pandemic, no sampling frequency was defined and the campaigns were carried out randomly. However, to represent the seasonal behavior of the Pandeiros River, at least one campaign was carried out in each period of the hydrological year (dry and rainy). In the campaigns carried out the flow rate was determined and samples of the water were collected to determine the suspended solids concentration (SS).

The flow rate was determined without the aid of a vessel in most campaigns. The conventional method was used, in which the flow rate is obtained as a product of the mean water velocity (determined using a flow probe, from the Global Water brand, model FP 111) and the cross-section area, as described in the publication "Measurement of liquid discharge in large rivers: technical manual" (Agência Nacional de Águas e Saneamento Básico, 2009). In some campaigns, it was not possible to carry out the process without the aid of a vessel. Therefore, the flow rate was determined using the acoustic method (Acoustic Doppler Current Profiler - ADCP), using the OTT Qliner2 flow meter.

Water samples were collected in five verticals of each cross-section using a US DH-48 sampler. Sample collection followed the procedures recommended by Carvalho (2008). The preservation of samples during transport and storage in the laboratory was performed according to the recommendations of the National Guide for Sample Collection and Preservation (Brandão, 2011).

The turbidity of the samples was determined in the field, using a portable turbidimeter (Digimed brand, model DM-TU). However, due to the unavailability of equipment, this variable was not determined in all campaigns. It was only possible to determine the turbidity of the samples in eight campaigns. The campaigns carried out and the variables measured are shown in Table 1.

The suspended solids concentration was determined at the Water Analysis Laboratory of the Water Resources Department of the Federal University of Lavras. The analyses followed the methodologies adapted from the American Public Health Association (2017).

Table 1. Date of sample collection, variables measured and number of samples taken.

Date	Turbidity			SS and Flow		
	US1	DS1	DS2	US1	DS1	DS2
05/01/2019	-	-	-	1	1	-
08/22/2019 - 08/23/2019	-	-	-	1	1	1
10/26/2019 - 10/27/2019	-	-	-	1	1	1
02/07/2020 - 02/09/2020	-	-	-	2	2	1
08/09/2020 - 08/10/2020	-	-	-	1	1	1
11/11/2020 - 11/12/2020	-	-	-	1	1	1
02/24/2021 - 02/25/2021	5	5	5	1	1	1
05/05/2021 - 05/06/2021	5	5	5	1	1	1
07/14/2021	5	5	5	1	1	1
10/19/2021	5	5	5	1	1	1
01/26/2022 - 01/27/2022	-	-	-	1	1	1
02/07/2022 - 02/09/2022	1	3	3	2	2	3
05/08/2022	5	5	5	1	1	1
10/11/2022	5	5	5	1	1	1
01/22/2023 - 01/24/2023	1	2	4	1	2	1

Sampling points

Three cross-sections were monitored along the Pandeiros River (Figure 2). The sampling points were chosen based on accessibility, the existence of monitoring structures of government agencies (Figure 3) and location relative to the Pandeiros Small Hydroelectric Plant (Pandeiros SHP) reservoir (upstream and downstream).

Sampling point US1 (15°28'59.50" S; 44°46'04.30" W; 3227.35 km^2) is located 3.0 kilometers upstream from the Pandeiros Small Hydroelectric Plant dam. In the same cross-section is the streamflow station under the responsibility of the National Water and Sanitation Agency (ANA, for its acronym in Portuguese) called *Usina do Pandeiros Montante* (code 44250000). This sampling point is located in a position that is not affected by the backwater of the Pandeiros SHP reservoir.

The sampling point DS1 (15°30'49.06" S; 44°45'15.40" W; 3622.52 km^2) is located 1.26 kilometers downstream of the dam, close to the place popularly known as *Cachoeira do Pandeiros*. In sampling point DS1 there is also a streamflow station called *Usina do Pandeiros*

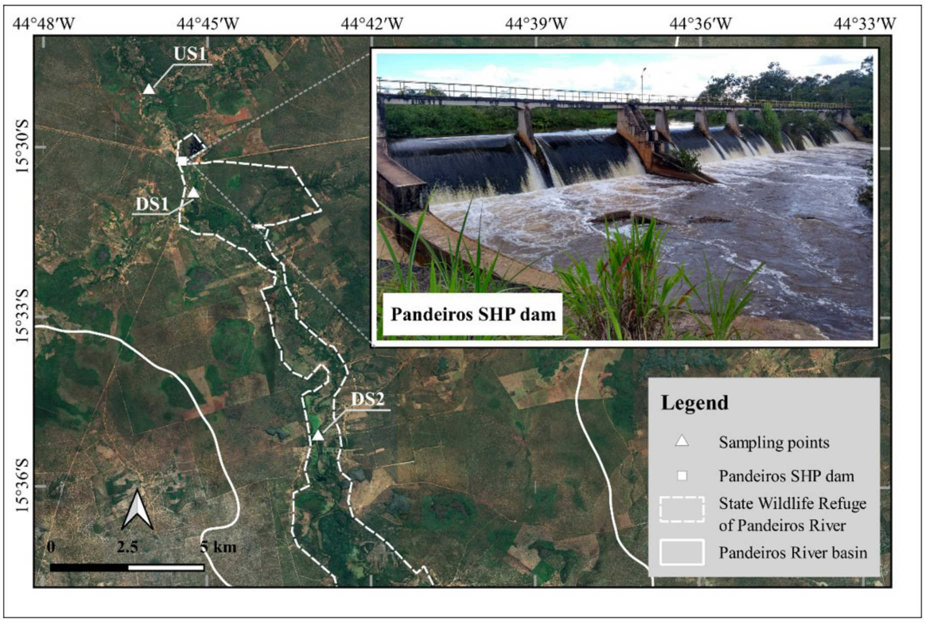

Figure 2. Location of sampling points.

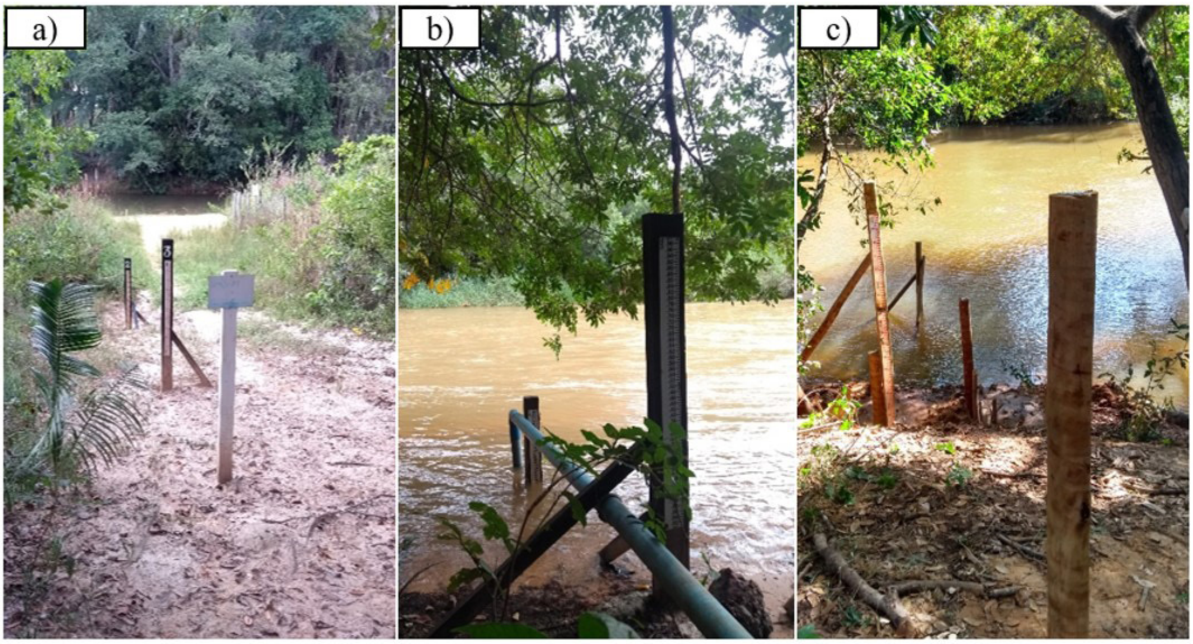

Figure 3. Monitoring structures installed on the monitored cross-sections: a) US1; b) DS1 and c)DS2.

Jusante (code 44252000), under the responsibility of the Minas Gerais Water Management Institute (IGAM, for its acronym in Portuguese).

Finally, sampling point DS2 (15°35'06.86" S; 44°42'58.32" W; 3776.95 km^2) was installed approximately 18.3 kilometers downstream of the dam, close to a crossing between the communities of *Campos* and *Casa Armada*. There are no structures from government agencies installed in this sampling point.

The DS2 sampling point was chosen because of its proximity to the area known as "*Pantanal Mineiro*". The "*Pantanal Mineiro*" corresponds to a flooded area that varies from approximately 30 km^2 (dry) to 50 km^2 (rainy) and is of great importance for the reproduction and development of the ichthyofauna of the São Francisco River (Nunes et al., 2009).

Data analysis

For data analysis and presentation, descriptive statistics were used (minimum, maximum, mean, standard deviation and coefficient of variation (CV)). The data was also subjected to non-parametric tests to compare periods (dry and rainy) and sampling points. Non-parametric tests were applied since the data did not show normality when subjected to the Shapiro-Wilk test (Royston, 1995; Shapiro & Wilk, 1965).

The Mann-Whitney test (Hollander & Wolfe, 1973) was used to compare periods. The Kruskal-Wallis test (Hollander & Wolfe, 1973) was used to compare sampling points. Once a significant difference was found using the Kruskal-Wallis test, the Dunn test was applied, with the p-value adjusted using the Bonferroni method to identify which groups differed. All tests were applied at a significance level of 5% and run on the RStudio software ("*stats"* package).

Model fitting

Models were fitted to determine the suspended solids discharge from flow rate data (suspended sediment rating curve) and to estimate the suspended solids concentration using flow and turbidity data.

The suspended solids discharge (Qss) was determined by the product between the suspended solids concentration (SS), given in mg/L, and the flow (Q), given in m^3/s, as described by Carvalho (2008) (Equation 1). The conversion factor 0.0864 was used to convert the unit of suspended solids discharge to Mg/d.

$$Q_{SS} = 0.0864 \times Q \times SS \quad (1)$$

The suspended sediment rating curves, which relate the flow rate to the suspended solids discharge, were fitted using a power function (Equation 2). In the model presented, "a" and "b" are fitting constants.

$$Q_{SS} = a \times Q^b \quad (2)$$

Discrepant data was excluded during the adjustment process to improve the coefficient of determination. To facilitate visualization and identification of discrepant values, the data were plotted using the logarithmic scale on both axes, as recommended by Carvalho (2008).

In addition to the curves relating flow and suspended solids discharge, a curve was fitted in terms of specific yield, relating the specific yield, given in L/(s km^2), and the specific suspended solids yield (SSY), given in kg/(d km^2). Data from the three sampling points were used to fit the curve that relates specific yield and specific suspended solids yield.

Two criteria were adopted to assess the quality of the curve fit and the need to generate more than one curve, as proposed by Lima et al. (2006) and observed in other studies. The criteria adopted were: a coefficient of determination value of at least 0.6 (Andrade, 2013; Bellinaso et al., 2007; Lima et al., 2006; Melo et al., 2020; Poletto, 2007); and visual analysis of the curve generated around the measured points (Lima et al., 2006; Menezes et al., 2021; Poletto, 2007).

To estimate the suspended solids concentration, three models were considered: linear, power and exponential models. The models related the flow and turbidity variables (independent) with the suspended solids concentration (dependent). To compare the fitted models, the following were used: the coefficient of determination and the mean absolute error (MAE) as described by Moriasi et al. (2015).

RESULTS AND DISCUSSIONS

Sediment transport characterization

The results of the Shapiro-Wilk test indicated that none of the variables had a normal distribution ($p < 0.05$). Therefore, non-parametric tests were used to compare different sampling points and periods (dry and rainy). The descriptive statistics of the measured variables are shown in Table 2.

As shown in Table 2, the suspended solids discharge varied between 1.9 and 765.2 Mg/d between sampling points. The highest value was observed in sampling point DS2, in a collection carried out after precipitation occurrence upstream of the sampling point. Although there are no records of this event using rain gauges, surface runoff was observed in the field in an ephemeral watercourse (Figure 4) upstream of the monitored sampling point, moments before the collection was carried out.

Precipitation led to the generation of surface runoff and, consequently, the dragging of particles into the watercourse, thus justifying the observed values. Furthermore, the Pandeiros River basin is characterized by a large number of gullies (Lima et al., 2019), which increase sediment input during the rainy season, resulting in higher sediment concentrations. According to Vercruysse et al. (2017), changes in precipitation and hydrology can cause variations in the suspended solids transport in rivers, especially on a seasonal scale. These changes can be intensified by alterations in land cover.

As in this study, Peixoto et al. (2020) found higher discharges and concentrations during the rainy season, in a study carried out in the Minas Gerais state, Brazil. The same behavior was observed by Garrido et al. (2018), in a study carried out in the Northeast region of Brazil.

The mean suspended solids concentration during the dry period was less than 10.5 mg/L, considered "Very Low (< 20 mg/L)" according to the classification proposed by Meybeck et al. (2003).

Table 2. Descriptive statistics for suspended solids (SS), flow rate (Q), suspended solids discharge (Qss) and specific suspended solids yield (SSY) variables.

		SS (mg/L)	Q (m^3/s)	Qss (Mg/d)	SSY (kg/d km^2)
US1	**Minimum**	3.5	5.2	2.0	0.6
	Maximum	190.0	22.6	316.6	98.1
	Mean	39.6	10.5	54.2	16.8
	Standard deviation	50.7	5.8	89.4	27.7
	CV (%)	127.9	55.2	164.9	164.9
	Mean (Dry)	8.8	6.5	5.1	1.6
	Mean (Rainy)	56.4	12.7	81.0	25.1
DS1	**Minimum**	3.0	5.5	1.9	0.5
	Maximum	169.0	35.0	460.5	127.1
	Mean	48.7	13.1	91.4	25.2
	Standard deviation	57.5	8.8	147.0	40.6
	CV (%)	118.1	66.8	160.9	160.9
	Mean (Dry)	8.5	7.3	5.6	1.5
	Mean (Rainy)	68.7	16.0	134.3	37.1
DS2	**Minimum**	6.6	5.3	3.7	1.0
	Maximum	504.3	28.0	765.5	202.7
	Mean	75.0	12.4	118.3	31.3
	Standard deviation	121.3	7.3	199.1	52.7
	CV (%)	161.8	58.6	168.3	168.3
	Mean (Dry)	10.5	6.7	5.9	1.6
	Mean (Rainy)	101.8	14.8	165.2	43.7

Legend: CV = coefficient of variation.

Figure 4. Ephemeral watercourse upstream of sampling point DS2 (a) during runoff and (b) after the end of runoff.

Similar behavior was observed by Garrido et al. (2018). According to Amaral et al. (2021), sediment concentration is intrinsically related to seasonality, and rainfall is one of the main factors contributing to sediment availability. According to the authors, low sediment concentrations during the dry season may be related to the state of conservation of riparian zones, which are one of the main sources of sediment during this period.

Regarding specific suspended solids yield, the general mean considering data from the two periods varied between 16.8 and 31.3 kg/(km^2 d), classified as "Low (10-50 kg/(km^2 d))" according to the classification proposed by Meybeck et al. (2003). In all sampling points, the mean specific suspended solids yield for the dry period was considered "Very Low (<10 kg/(km^2 d))" and "Low" for the rainy period. Only in one campaign carried out in sampling point DS2 was the specific suspended solids yield considered "High (200-1000 kg/(km^2 d))". In other sampling points, the highest values observed were classified as "Moderate (50-200 kg/(km^2 d))".

When the Mann-Whitney test was applied, using data from all sampling points together, a significant difference ($p < 0.05$) was observed between the dry and rainy periods for all variables. When applying the test using data from isolated sampling points, no significant difference was observed ($p > 0.05$), except for the flow variable in sampling point DS1. The Kruskal-Wallis test indicated that there was no significant difference between sampling points for all variables analyzed.

As in this study, Vanzela et al. (2012) found no significant difference between the dry and rainy periods when assessing the suspended solids concentration in the same sampling point. However, in one of the basins studied, a difference was observed between the periods when analyzing the total solid yield.

Suspended sediment rating curve

Three suspended sediment rating curves relating flow to suspended solids discharge were fitted (Figure 5), one for each sampling point. A suspended sediment rating curve relating specific yield to specific suspended solids yield was also fitted (Figure 6), using data from all sampling points.

Discrepant data was discarded to improve the coefficient of determination of the sediment rating curves. An example of discrepant data is the data collected on 01/27/2022 in sampling point DS2. This collection was influenced by the contribution of an ephemeral stream (Figure 4), which resulted in a high suspended solids discharge (765.2 Mg/d).

In all sampling points, the coefficients of determination were greater than 0.94, indicating a good fit of the suspended sediment rating curves to the data and meeting the criteria proposed by Lima et al. (2006).

According to Asselman (2000), the coefficients "a" and "b" have no physical meaning, but are believed to be related to factors such as the erosion severity, or the availability of sediment, the power of the river to erode and transport the available material, and on the extent to which new sediment sources become available in weather conditions that cause high flows.

According to Zhang et al. (2012), the building of dams on the Pearl River in China resulted in a decrease in sediment supply. This has led to an increase in the rating coefficient "a" and a decrease in the rating exponent "b". According to Lima et al. (2004), the higher value of this constant indicates a rapid response of the suspended sediment discharge in relation to flow variations. According to the authors, for basins with large contributing areas, this constant generally varies between 1 and 3. According to Iadanza & Napolitano (2006), high values of the "b" coefficient indicate rivers in which a small increase in flow results in a large increase in suspended solids discharge.

In the Pandeiros River, the value of the constant "b" varied between 3.00 and 3.28 between sampling points. The observed values in the Pandeiros River are related to the presence of gullies in the basin, which are responsible for producing a large amount of sediment. Thus, small variations in flow lead to substantial variations in suspended solids discharge. Lima et al. (2019) report the existence of at least 215 gullies in the Pandeiros River basin.

Regarding adjustments involving flow and suspended solids discharge, as in this study, several authors adopted the power function in tracing the key curves. Some examples are the studies carried out by Chella et al. (2005), Leli et al. (2011), Melo et al. (2020), Menezes et al. (2021) and Silva et al. (2021). However, other models can be used when the power model does not present a good fit, such as the linear model, which showed better results in the study carried out by Sirqueira et al. (2022).

According to Lima et al. (2006), there are cases in which more than one curve is necessary to adequately represent the relationship between flow and suspended solids discharge, and the curves may vary according to the period or flow. Tilahun et al. (2023) emphasize that to obtain estimates of sediment production with low uncertainty, it is necessary to develop curves on appropriate temporal scales. According to Hapsari et al. (2019), data separating between seasons and the increasing sampling frequency may be necessary to improve estimates. However, in some cases, the separation between dry and rainy seasons may not improve the adjustment, as observed by Silva et al. (2021).

In this study, only a single sediment rating curve was fitted for each section, since dividing it into periods or flow ranges would result in curves with a reduced number of data. In addition, the coefficient of determination values met the established criterion with an R^2 greater than 0.6.

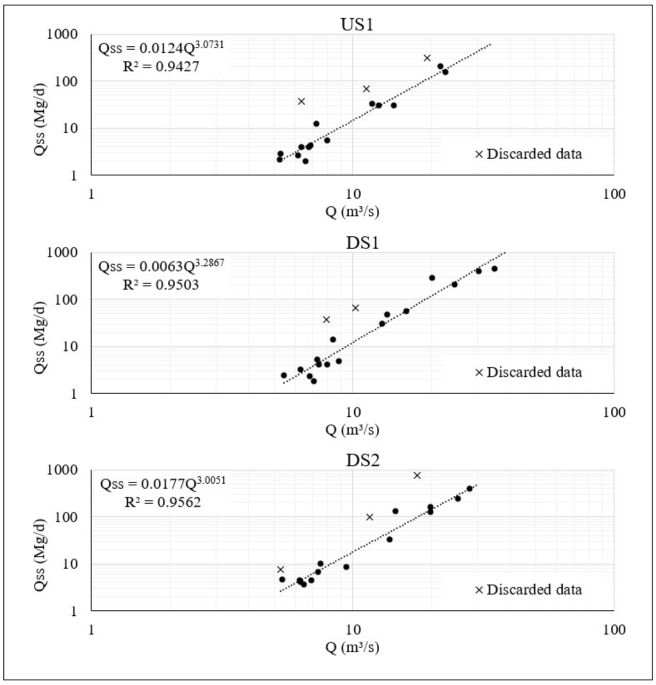

Figure 5. Suspended sediment rating curves relating flow (Q) and suspended solids discharge (Qss), plotted with axes on a logarithmic scale.

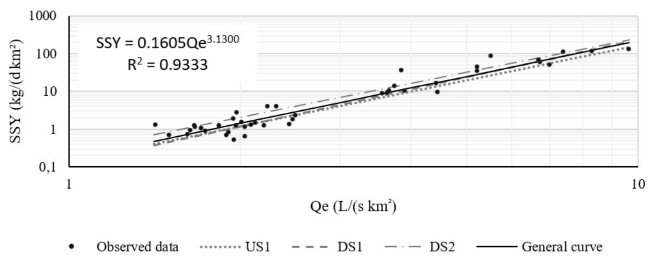

Figure 6. Suspended sediment rating curve relating specific yield (Qe) and specific suspended solids yields (SSY), plotted with axes on a logarithmic scale.

As in this study, Peixoto et al. (2020) adjusted suspended sediment rating curves for 4 cross-sections of the Jordan River, in the southeast of Brazil, and obtained R^2 higher than 0.87. The authors adjusted a single curve per sampling point. In contrast, Garrido et al. (2018) adjusted two curves for a single sampling point, in the Northeast of Brazil, one representing the dry period and the other the rainy period. The R^2 values were 0.81 and 0.90. Melo et al. (2020) adjusted suspended sediment rating curves for 3 stations located on the São Francisco River, Brazil, and obtained R^2 varying between 0.64 and 0.89. In some streamflow stations, the authors adjusted more than one curve for different periods (years). As for the coefficient of determination, the value obtained by Louzada et al. (2022) was 0.80, considered good by the authors.

The coefficient of determination of the general curve, adjusted using specific yield and specific suspended solids yield (Figure 6), was 0.93, indicating a good fit. As in this study, Chella et al. (2005) adjusted a curve relating specific yield and specific suspended solids yield, however, the value of the coefficient of determination obtained by the authors was 0.55, lower than the value recommended by Lima et al. (2006). The authors used data from four sampling points located in the same basin in southern Brazil.

Regarding data dispersion, Chella et al. (2005) suggest that dispersal may be associated with factors such as land use, precipitation and erosion control, which vary greatly in time and space. Louzada et al. (2022) also associated factors such as vegetation cover, soil characteristics and terrain slope with variations in sediment concentration.

According to Aleixo et al. (2020), the heterogeneity of watershed and precipitation events may result in very different suspended sediment concentrations for the same flow values. Asselman (2000) suggests that data scatter is related to, among other things, variations in sediment supply, caused by seasonal effects, antecedent conditions in the watershed and differences in sediment availability at the beginning or end of a flood. Vercruysse et al. (2017) state that hydro-meteorological factors such as rainfall and river discharge are the main agents of sediment transport.

In the Pandeiros River basin, several factors are related to the variability of sediment concentration. The main ones are precipitation (seasonality) and land cover characteristics. In addition to the presence of gullies, already mentioned, anthropogenic activities such as burning, road opening and deforestation alter the characteristics of the land cover and affect the dynamics of sediment transport. These activities were reported in studies carried out by Borges and Costa (2022), Fonseca et al. (2011) and Nunes et al. (2009).

Another factor that may be related to data dispersion is the occurrence of the phenomenon of hysteresis. According to Leli et al. (2011), "hysteresis is the effect in which the same flow values correspond to different suspended sediment concentration values". According to the authors, hysteresis can occur in both the dry and rainy seasons.

Models for estimating solids concentration

Among the three models adjusted to estimate the suspended solids concentration using the flow rate, the power function presented the highest values for the coefficient of determination. Regarding the models that used turbidity to estimate the suspended solids concentration, the highest coefficients of determination were obtained by the linear models. The value of the coefficient of determination and mean absolute error obtained for each of the adjustments can be seen in Table 3.

All the adjusted models were significant at a 5% probability. In general, the models that used turbidity to estimate the suspended solids concentration had a higher coefficient of determination when compared to the models that used flow. The exponential model presented the lowest values in both cases.

Although the power models that utilized turbidity to estimate the concentration of suspended solids did not have the highest coefficients of determination, they had the lowest mean absolute errors. However, the difference was no more than two units. According to Singh et al. (2004), the mean absolute error describes the difference between observed and estimated values in the unit of the variable. The authors suggest that values lower than half of the standard deviation of the observed values may be considered low, while values close to zero indicate a perfect fit. For all models fitted in this study, the mean absolute error was lower than the standard deviation of the observed data.

As in this study, Stutter et al. (2017) also obtained higher coefficients of determination in the fit between suspended solids

Table 3. Coefficients of determination (R^2) and mean absolute error (MAE) of the models fitted to estimate the suspended solids concentration (SS) using the flow (Q) and turbidity (T) variables.

Sampling point	Q × SS			T × SS		
	Lin.	Pot.	Exp.	Lin.	Pot.	Exp.
			R^2			
US1	0.8738	**0.8807**	0.8620	**0.8997**	0.8960	0.8044
DS1	0.8411	**0.9006**	0.8158	**0.9544**	0.8858	0.6875
DS2	0.8851	**0.9047**	0.8766	**0.9611**	0.9279	0.8483
All	0.8589	**0.8834**	0.8284	**0.9185**	0.8843	0.6930
			MAE			
US1	7.62	**6.10**	7.10	3.43	**3.04**	8.17
DS1	13.35	**16.53**	29.90	6.00	**4.97**	23.41
DS2	11.71	**9.90**	17.07	7.12	**5.99**	27.57
All	11.73	**11.31**	22.07	7.64	**5.74**	24.80

Legend: Exp. = Exponential; Lin. = Linear; Pow. = Power.

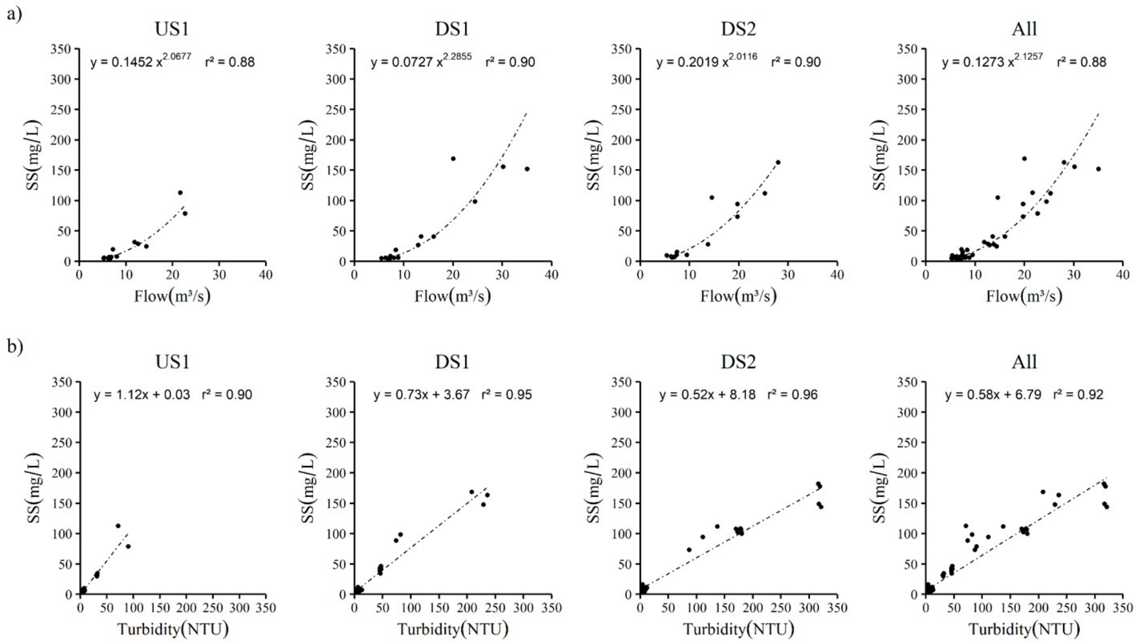

Figure 7. Models relating (a) flow and suspended solids concentration and (b) turbidity and suspended solids concentration.

concentration and turbidity when compared to the fit between suspended solids concentration and flow rate and concluded that suspended solids concentration was better related to turbidity. Sirqueira et al. (2022) observed coefficients of determination of up to 0.88 when relating turbidity and suspended solids concentration, while López et al. (2021) observed values varying between 0.53 and 0.58. Ferreira et al. (2023), Gall et al. (2022) and Hoffmann & Oliveira (2018) also observed a positive correlation between turbidity and suspended solids, in contrast, Quinelato et al. (2020) found no correlation between turbidity and suspended solids concentration. Putri & Arisalwadi (2023) found that with an increase in the suspended solids concentration, there was an increase in turbidity, indicating a directly proportional relationship between the variables.

Several authors have concluded that turbidity can be used to estimate the suspended solids concentration, such as Latuf et al. (2019), Rügner et al. (2013) and Villa et al. (2019). Although turbidity is widely used to estimate suspended solids concentration, factors such as particle size distribution, particulate organic matter concentration (Bright et al., 2020), particle shape and the presence of phytoplankton, can influence the turbidity-suspended solids relationship (Bilotta & Brazier, 2008). Therefore, high turbidity levels may not correspond to high concentrations of suspended solids (Bilotta & Brazier, 2008).

Regarding adjustments involving flow, Leli et al. (2011) state that low values of the coefficient of determination may be due to the phenomenon of hysteresis, in which different suspended solids concentrations can be observed for the same flow rate value. The authors found this phenomenon in a study carried out in the Southern Region of Brazil. Ziegler et al. (2014) also reported the occurrence of hysteresis as one of the factors that affect the relationship between flow and suspended solids.

Most of the models adjusted with the data from a single sampling point had a higher coefficient of determination than the one obtained when fitting the data from all the sampling points. The exceptions were the exponential and linear models using flow rate, adjusted for sampling point DS1, the exponential model adjusted for sampling point DS1 using turbidity, and the linear model adjusted for sampling point US1 using turbidity.

The higher values of the coefficient of determination observed for specific sampling points, as well as the different adjustment coefficients (Figure 7), indicate that the relationship between the variables can change between cross-sections and that adjustment is necessary for the conditions of the location of interest. As in this study, Villa et al. (2019) found that the models adjusted for specific sampling points showed better results than the models adjusted using data from different sampling points together. However, the authors pointed out that in some cases the general models still presented coefficient of determination values close to the values obtained for the models adjusted for the specific sampling points.

Stutter et al. (2017) suggest that the models should be calibrated for specific sampling points since there is variation in the adjustment coefficients between locations. Rügner et al. (2013) stated that turbidity can be used to estimate suspended solids concentration if the correlation between the variables is determined. For Pandeiros River we consider that in the absence of available data for the location of interest, models adjusted with data from different sampling points can be used to estimate the suspended solids concentration.

CONCLUSIONS

The data obtained allowed us to conclude that monitoring suspended solid discharge using the suspended sediment rating curve in the Pandeiros River is viable. Furthermore, the curve relating specific yield and specific suspended solids yield presented a good fit ($R^2 = 0.93$) and can be considered an alternative for estimating suspended solids discharge in cross-sections that do not have sedimentometric data, through the flow monitoring.

It was also evident that both flow rate and turbidity can be used to estimate the suspended solids concentration in the Pandeiros River. However, despite the models that used data from all sampling points presenting a coefficient of determination above 0.88, it is recommended that, to use turbidity and flow to estimate the suspended solids concentration, relationships between the variables should be established for the site of interest, since the relationships may vary from one site to another.

Finally, despite the good quality of the adjustments obtained in this study, it is recommended to continue monitoring and increase the sampling frequency, especially during the rainy season, to capture possible temporal variations in the relationships studied and increase the accuracy and representativeness of the suspended sediment rating curves and adjusted models.

ACKNOWLEDGEMENTS

This study was developed in partnership with Cemig and Aneel's Research and Development Program (P&D GT0611).

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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Editor-in-Chief: Adilson Pinheiro

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