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Applicability of sediment rating curves: analysis in the state of Rio Grande do Sul

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A B S T R A C T

The transport of sediments is present in all watercourses, occurring naturally, however, in different ways and characteristics. Its quantification in watersheds becomes extremely important for the planning and management of water resources. The sediment rating curve, which empirically describes the relationship between stream flow and suspended sediment concentration (Css), is an alternative tool to the lack of continuous monitoring of sediment transport. The aim of this research was to evaluate the use of rating curves in sedimentometric stations in Rio Grande do Sul, Brazil. Three Css data handling scenarios were tested for the analytical fitting of sediment rating curves considering a power function as follows: complete data sets, data sets subdivided into 10-year periods and subdivided into stream flow ranges. The approaches adopted in the present study were evaluated taking as reference 58 sedimentometric stations in the state. The goodness-of-fit tests used in this study - coefficient of determination, Relative Average Percentage Error and Nash Sutcliffe coefficient, indicated that the best results of the estimation of sediment transport were observed when the sediment rating curve was fitted to the 10-year period data set.

Keywords: Sediment transport; Suspended sediment concentration; Hydrological modeling.

Aplicabilidade de curvas-chave de sedimentos: análise no estado do Rio Grande do Sul

R E S U M O

O transporte de sedimentos está presente em todos os cursos d´água, ocorrendo de maneira natural, porém, de formas e características diferentes. Sua quantificação, em bacias hidrográficas, se torna extremamente importante para o planejamento e gestão de recursos hídricos. O modelo da curva-chave de sedimentos é uma ferramenta alternativa à ausência de monitoramento contínuo de transporte de sedimentos amplamente empregada, que, empiricamente, descreve a relação entre vazão e a concentração de sedimentos. O objetivo desta pesquisa consistiu em avaliar a utilização de curvas-chave em estações sedimentométricas do Rio Grande do Sul, Brasil. Foram testados três cenários de manipulação dos dados de concentração de sedimentos em suspensão para o ajuste das curvas-chave de sedimento para 58 estações do estado, ajustando analiticamente à uma função de potência: dados completos, subdivididos em período de 10 anos e subdivididos em intervalos de vazão. Os testes estatísticos de eficiência do coeficiente de determinação, Erro Relativo Percentual Médio e coeficiente de Nash Sutcliffe demonstraram que os melhores resultados da estimativa de transporte de sedimentos foram observados quando o modelo da curva-chave testado foi aplicado aos dados divididos em períodos de 10 anos.

Palavras-chave: Transporte de sedimento; Concentração de sedimentos em suspensão; Modelagem hidrológica.

Introduction

Bearing in mind the proper management of water resources, the study and understanding of hydro-sedimentological processes in watersheds are of great importance to minimize the negative effects of water erosion. These processes are part of an open cycle that involves the separation, displacement, transport, and deposit of solid particles present on the surface of the basin (Van Pelt et al., 2017).

The transport of solid particles in watercourses, also called sediment transport, is closely associated with geomorphological, climatic, use, occupation and soil management factors and agricultural practices of a watershed (Toledo, 2023). To be monitored and evaluated, the transport must be divided into suspended sediments, in which the most predominant portion of particles is fine and light remaining suspended, and bedload, which comprises a smaller portion, but of coarser sediments that move along the bottom of the watercourse (Carvalho, 2008; Poleto, 2014; Zhang et al., 2012).

In order to understand the dynamics of a watershed, part of the sediment transport can be monitored based on the concentration of suspended sediments (Css). Its quantification is important, as it influences the quality of the water, the storage capacity of reservoirs (Ghafari et al., 2017), fishing, drainage, eutrophication of watercourses due to excess nutrients (Zhang et al., 2012), sedimentation of canals and silting up of harbors, as well as other ecological and recreational impacts (Sadeghi et al., 2008).

In Brazil, the National Water and Sanitation Agency (ANA) is responsible for making available the information collected by the National Hydrometeorological Network (RHN). RHN gathers climatological and hydrological data from 12,731 rainfall gauges and 9,748 fluviometric stations. The stations where sediment monitoring is carried out are called sedimentometric stations and their lower availability, compared to fluviometric stations (stage/stream flow), is associated with operational and financial difficulties (Carvalho, 2008).

The difficulties to ensure sediment monitoring are associated with the high cost of implementing and maintaining sampling, given the need for many field trips, a high number of measurements, great operational care, from the choice and maintenance of equipment, specialized technical staff and laboratory analyses. Considering the need to quantify the transport of sediments in different watersheds, in a more accessible way and in view of the operational difficulties mentioned above, alternative tools such as empirical models of sediment rating curves have been applied to represent the relationship between stream flow and Css (Asadi et al., 2021; Bhattacharya, 2024; Dehghan-Souraki, 2024; Gao et al., 2018; Hapsari et al., 2019;). In other words, the sediment rating curve is used due to the lack of continuous monitoring of sediment transport (Sadeghi et al., 2008).

As such, water resources professionals often use it to convert hydrographs into sedigraphs (Mohanty & Biswal, 2022). Even with the use and application of the sediment rating curves, it is necessary to carry out hydrological campaigns for sediment sampling in order to obtain values for determination the rating curves (Billi & Spalevic, 2022). Despite its general use, several problems are recognized and must be taken into account by professionals in the field when using the sediment rating curve technique (Barberena et al., 2023). These limitations and difficulties are related to the change in the relationship between stream flow and Css in the data used, to the time lag that occurs between the hydrograph and the sedigraph but may not be represented, such as the impact of hysteresis (Yu et al., 2023), in addition to the choice of the function model for fitting the observed data, as well as the dispersion of values over the regression line, with the possibility of extrapolating results that are not included in the observed values (Asselman, 2000; Hapsari et al., 2019; Hassanzadeh et al., 2018; Sadeghi et al., 2008; Yu et al., 2023).

Invariably, a good relationship is sought, that is, a rating curve presents a high correlation with the data (Sadeghi et al., 2008). However, due to geomorphological changes and/or soil use and management, the relationship between Q and Css can be modified (Bihonegn & Awoke, 2023), presenting changes over time, in which rating curves used in the past do not always represent the current relationship between Q and Css adequately (Zhang et al., 2012). Another setback of sediment rating curves is that the effect of hysteresis is not always identified, representing the delay in the evolution of a physical phenomenon in relation to another (Minella et al., 2011; Yang; Lee, 2018). In general, the dynamics of Q and Css during events do not show simultaneity, in which the peak value of Q does not necessarily occur at the same instant as that of Css (Minella et al., 2011).

Uncertainties in the predicted values may also be related to the statistical form used to fit the sediment rating curves to the observed values of stream flow and Css (Asselman, 2000; Barberena et al., 2023). Although this technique has been widely used for a wide variety of purposes, sediment rating curves might result in underestimates and overestimates. According to Cohn et al. (1992), for example, Css values are normally underestimated when rating curves are obtained through the least squares regression of log-transformed variables. In addition, discrepancies in the the Css values derived from sediment rating curves originate in the extrapolation at high stream flows, which is related to the quantity and quality of the observed data (Iadanza & Napolitano, 2006).

However, in practice, the extrapolation of rating curves is inevitable and it is important to quantify the uncertainties that result from their use. Sadeghi et al. (2010) argue that coefficients of determination (R^2) lower than 50%, for the models tested in the Khamesan basin, represented a sign of inability of the rating curves to estimate sediment transport. Likewise, inaccuracies are associated with the dispersion of values over the regression line, which might be caused by variations in sediment delivery due to seasonal effects, antecedent moisture conditions in the watershed and differences in sediment availability at the beginning or at the end of a significant rainfall event (Asselman, 2000).

Shojaeezadeh et al. (2024) researched the incorporation of hydro-climate variables (flow, precipitation and temperature) as input data to improve predictions of suspended sediment concentration. The authors demonstrate that the integration of climate data and flow data has proven to be effective in forecasting improving understanding of sediment transport dynamics. Nonetheless, these factors are not accounted for the rating curve, however, there is still a lack of studies that assess the representativeness of such curves.

Furthermore, statistical analyses have demonstrated that results from rating curves can be incorrectly obtained when estimated from the use of the entire data set (Asselman, 2000; Gao et al., 2018; Girolamo et al., 2015). To correct this inadequacy, several ways of subdividing the data set have recently been applied (Hassanzadeh et al., 2018; Maheshwari & Chavan, 2022; Zeng et al., 2018). Zhang et al. (2012) suggest separating the stream flows into periods (of years, dry and wet seasons, quarters, months, seasons of year or spring-summer and fall-winter) such that rating curves can be plotted separately. Maheshwari and Chavan, (2022) based on the proposed approach, concentrations were calculated considering several sediment classification curves fitted to total, seasonal, stage and season-stage data sets.

In this discussion, it is important to analyze the viability of the sediment rating curve method in representing sediment transport in monitored watercourses, demonstrating a strong correlation between flow rate and suspended sediment concentration. Additionally, it is crucial to assess the effectiveness of the equation utilized in the sediment rating curve method in representing the analyzed data, and to investigate whether variations in the input dataset enhance the estimation. However, the hydro-sedimentological dynamics and the performance of sediment rating curves in different forms are therefore different for each location, making it important to investigate regions of interest.

The state of Rio Grande do Sul makes an expressive contribution to national agricultural production, destined for both the domestic market and export (Feix & Leusin Júnior, 2019). In this way, the conception of hydro-sedimentological dynamics and studies of soil erosion are of fundamental importance for this region. In view of the availability of 87 sedimentometric stations for the state and the scarcity of studies on this subject, the objective of this research was to evaluate the feasibility of rating curves of suspended sediments using different alternatives of subdivisions, based on data analysis of sedimentometric stations available for the state of Rio Grande do Sul, Brazil.

Material and methodology

Description of the study area

The state of Rio Grande do Sul (RS), comprised by the parallels 27° 04' 49” and 33° 45' 00” South and by the meridians 49° 42' 22” and 57° 38' 34” West, is located in the South of Brazil (Figure 1), and is bounded by the state of Santa Catarina, Argentina and Uruguay, in addition to the Atlantic Ocean, with an area covering 281,738 km² (IBGE, 2016) within 497 municipalities. According to the Köppen classification, the region's climate is classified as “Cf” or humid temperate, with well-distributed rainfall throughout the year. In most of the state, the climate type “Cfa” prevails, with the temperature of the hottest month above 22°C (Sparovek et al., 2007).

Hydrological data used

ANA provides Css data from sedimentometric monitoring stations where hydrological campaigns are carried out to sample suspended sediments contained in a given volume of water. Data sets from sedimentometric monitoring stations are still little used compared to those of fluviometric and pluviometric stations managed by ANA. A survey of these stations available for the state of Rio Grande do Sul is illustrated in Figure 1. The Css data made available by ANA come from hydrological campaigns of stream flow measurement and sampling of suspended sediments, provided in the unit of mg L-

1, whose stations are monitored by responsible entities.

After the initial survey of 87 sedimentometric stations for the state, those that did not contain Css data were identified and eliminated. The stations with available data were selected and had their data organized to verify the extent of the data set, quantify the stations that remain in operation and those that ended the measurements/sampling. In addition, the series of these stations were used to fit the coefficients of the corresponding sediment rating curves.

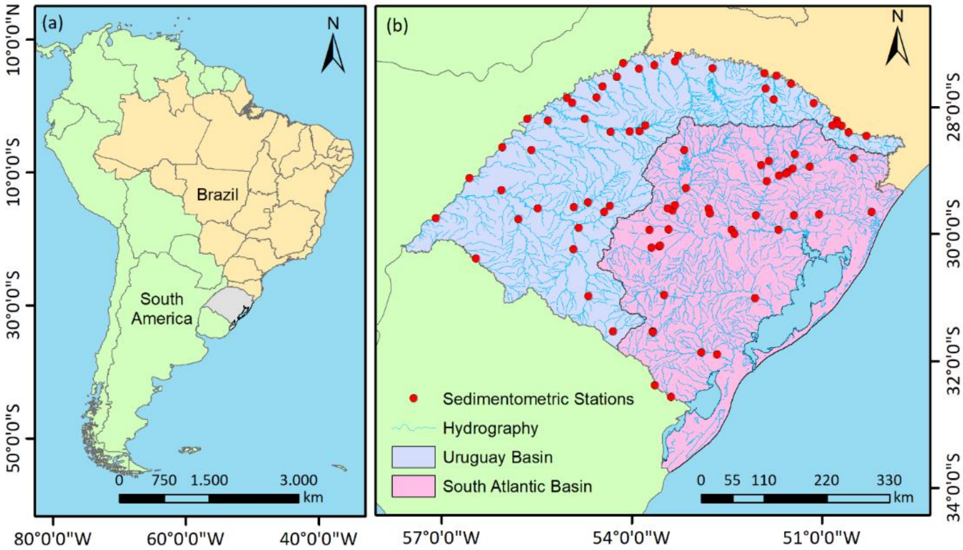

Figure 1. (a) Location of the state of Rio Grande do Sul (RS) in Brazil and South America and (b) location of sedimentometric stations recorded in the ANA hydrological information system, in the context of the hydrographic regions of Uruguay and South Atlantic, within Rio Grande do Sul.

Associated with the period of data referring to the hydrological campaigns for the determination of Css, for each sedimentometric station, series of annual average stream flow were organized with the aid of the System of Hydrological Data Acquisition and Analysis (SYHDA) (Vargas et al., 2019). These series were checked for temporal trend following the Mann-Kendall test (Mann, 1945; Kendall, 1975), through the routine "Mann-Kendall with Missing Values and Same Values" developed by Lee (2020) in MATLAB (MATLAB, 2013), with the objective to verify the existence of trends in the historical stream flow series for the considered periods. The Mann-Kendall test is widely used in research to examine trends in historical series of different hydrometeorological variables (Blain & Camargo, 2012; Blain & Meschiatti, 2014; Li et al., 2017; Gao et al., 2017; Cassalho et al., 2017; Dorneles et al., 2019). For this research, the results of the Mann-Kendall test, applied to each of the series of annual average stream flows, served as a requirement for the continuity of the modeling.

Fitting of suspended sediment rating curves

Suspended sediment rating curves should be based on measurements at all stream flow conditions, including a sufficient number of measurements taken at high stream flow conditions. In view of this, we decided to fit the rating curve for each of the sedimentometric stations using: i) all the data; ii) 10-year periods considering the beginning of the measurements as a basis; and iii) stream flow ranges. The latter form of data division for the fitting of rating curves, discussed and recommended by several authors (Asselman, 2000; Girolamo et al., 2015; Sadeghi et al., 2008; Zeng et al., 2018), consists of splitting the data into subsets defined according to the stream flow conditions for each of the stations, defined as: high stream flows, average stream flows, and low stream flows. For this, the dataset was divided into three ranges of stream flow exceedance frequency, as suggested by Girolamo et al. (2015): (a) from 0 to 20% defined as high stream flows; (b) from 20 to 70% considered average stream flows; and (c) above 70% determined as low stream flows. The stream flow values considered limiting in the ranges, for each of the subsets, were defined for each of the series following the exceedance frequency.

For those stations that presented a smaller amount of observed data, a small sample was used in each range when applying the subdivision in the three aforementioned exceedance frequency ranges, making it impossible to fit the rating curve due to the small amount of data. In view of this, for the stations that presented this characteristic (73480000, 74800000, 76120000, 88680000), we opted to divide the data into only two ranges, therefore considering the exceedance frequency in 50% as threshold to define high and low stream flows.

Comparison of the fitted curves at different periods of hydrological campaigns provides an indication of the robustness of the sediment rating curves under slightly different times as well as for stream flow conditions. The suspended sediment rating curve, for each monitoring station, as recommended by Asselman (2000), Zhang et al. (2012) and Hassanzadeh et al. (2018), was analytically fitted to a power function (Equation 1).

$$Css = a\,Q^{b} \qquad \text{Eq. 1}$$

where:
Css: concentration of suspended sediment (mgL^{-1});
Q: stream flow (m^{3} s^{-1});
a and b: fitting coefficients.

Next, different statistical criteria were applied to assess the adequacy of the rating curve models to the data set. The average percentage relative error (ERP) was estimated to evaluate the performance of each analyzed rating curve. The ERP was established to compare the Css values (ERPCss – Equation 3) estimated by the rating curve with those observed in the hydrological campaigns, as recommended by Horowitz (2003) and Sadeghi et al. (2008), ranging from zero to infinity. Css values closer to zero are expected, indicating smaller associated errors.

$$ERPCss = \frac{\sum\left[\frac{Css_{Calc} - Css_{Obs}}{Css_{Obs}}\right]}{N} * 100 \qquad \text{Eq. 2}$$

where:
CssCalc: suspended sediment concentration estimated by the rating curve model (mg L^{-1});
CssObs: observed suspended sediment concentration (mg L^{-1});
N: number of observations.

Likewise, the determination coefficient (R^2) (Levine et al., 2000; Yadolah, 2008) was used to assess the quality of the fit of the rating curve models (R^2Css - Equation 4). The R^2, which can vary from 0 to 1, is a descriptive measure of the quality of the fitting obtained, that is, the variability in the data that is explained by the fitted regression model. The value of 1 indicates a perfect relationship between the observed data and that obtained by the fitted regression model (Girolamo et al., 2015; Zheng et al., 2012; Zeng et al., 2018).

$$R^2 Css = \left(\frac{\sum (Css_{Calc} - \overline{Css_{Calc}})\,(Css_{Obs} - \overline{Css_{Obs}})}{\sqrt{\sum (Css_{Calc} - \overline{Css_{Calc}})^2 . \sum (Css_{Obs} - \overline{Css_{Obs}})^2}} \right)^2 \qquad \text{Eq.3}$$

where:
$\overline{Css_{Obs}}$: mean of observed suspended sediment concentrations (mg L^{-1}).

Another efficiency criterion used was that of Nash and Sutcliffe (NS), as defined by Nash and Sutcliffe (1970), described in Equation 5, which determines the efficiency of a model in comparison with the average value observed.

$$NSCss = \frac{\sum(Css_{Obs} - \overline{Css_{Obs}})^2 - \sum(Css_{Calc} - Css_{Obs})^2}{\sum(Css_{Obs} - \overline{Css_{Obs}})^2} \qquad \text{Eq.4}$$

The NS statistic indicates whether the applied model provides better estimates than applying the observed average value. NS values range from minus infinity to 1, where 1 represents a perfect agreement between observed and calculated suspended sediment concentration values. Negative values indicate that the mean value of the observed Css is a better estimate than those obtained by the model (Asselman, 2000).

Results and Discussion

Quantitative and qualitative analysis of the monitoring network

Following the proposed criteria, it was identified that 87 sedimentometric stations were duly registered in the Hidroweb/ANA portal when this research was carried out, considering an analysis until the end of 2017 for the state of Rio Grande do Sul (RS). However, it was found that 63 out of these actually had data available for analysis. The others were registered in the system, however, they did not contain Css data.

A considerable amplitude of the data can be observed, following the maximum and minimum values of Css for the sedimentometric stations of RS. Lin et al. (2022) discuss that Css undergo significant periodic variations on multiple time scales in response to various cyclical forcing factors. The authors demonstrate that identifying key periods and extracting corresponding amplitudes and phases can greatly assist in the effort to characterize the representative portrait of Css, which contributes to a deeper physical interpretation.

The stations present values ranging from low maximum Css, such as those from station 86100000 - Passo do Gabriel (24.26 mg L-1) to high values such as the maximum value observed at station 76440000 - Jaguari (1965.5 mg L-1). Likewise, minimum values of high and low Css are observed, as in station 76380000 - Cacequi, with a minimum value of 35.33 mg L-1, an average of 85 mg L-1, up to the minimum observed for all stations which was presented by station 86410000 - Passo Barra do Guaiaveira (minimum value of 0.06 mg L-1).

The World Meteorological Organization (WMO, 2008) recommends a minimum density of 1 sedimentometric station every 12,500 km², considering an average for coastal, mountainous, flat and undulating inland regions. Considering the survey carried out, judging for the RS area, the number of stations made available by ANA is in accordance with the suggested minimum density. However, this does not mean that this value is sufficient for engineering projects and water resource management in the region. The stations with and without data availability, as well as the current operational situation of the stations and the extent of the data, are shown in Figure 2.

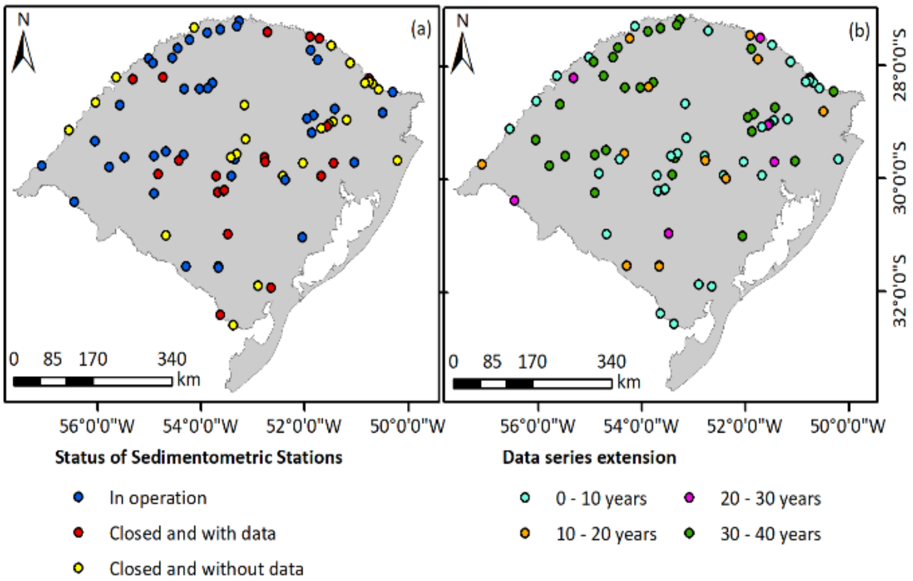

Figure 2. (a) Operating status of the sedimentometric stations considering the year 2017 as a query; (b) Extension of the sedimentometric data of each station considered until the year 2017.

One can notice in Figure 2 that most stations with available data are in operation (42), that is, with current data records. This is interesting from the point of view of continuity in updating the rating curves, given the typically pronounced inter-variability in river flow and sediment load export from river basins, stemming from climate variability and alterations in land surface characteristics (Gao et al., 2021).

The other stations (21) ended the hydrological campaigns or have an old date as the last record. Of the 63 stations, 48% have data covering a period between 30 and 40 years. Of these, only two are no longer in operation, while the others are still being monitored. This situation is extremely important, as the greater the extent of the data, presumably, the greater the range of stream flows (dry and rainy periods), increasing the reliability of the rating curves (Fu et al., 2020; Zhang et al., 2012). As a continuity criterion for the fitting of the rating curves, it was identified that only one (75186000) of the 63 sedimentometric stations presented temporal trend in the series of annual average stream flow according to the Mann-Kendall test. This station was eliminated from the analyses.

Fitting of suspended sediment rating curves

For the fitting of the sediment rating curves, the data was separated into: Strategy 1 - using complete Css data, Strategy 2 - data subdivided into 10-year periods, and Strategy 3 - data subdivided into stream flow ranges, as suggested by several authors (Barberena et al., 2023). Afterwards, the values of coefficients a and b were estimated with basis on the Css data for each of the 58 analyzed stations. This occurred because station 75186000 was eliminated from the analysis because it presented temporal trend according to the Mann-Kendall test, which served as a requirement for the other modeling steps. For the others (85620000, 85625000, 87035000 and 88220000), the rating curve was not obtained, as these have few hydrological campaigns available (less than 5 measurements). This would make the application of the rating curve methodology unfeasible. Tables 1 and 2 present a summary of the results of applying the statistical indices, NS and R^2 and ERP, respectively, for the 3 strategies.

Table 1 - Number and percentages of stations with positive NS, for the fitting of the rating curve model to the Css data, for the scenarios with complete data, 10-year periods and stream flow range for the analyzed stations.

Statistical indidices	Complete data	10-year period	Streamflow range
NSCss (N+)	29	105	51
NSCss % (+)	50	62	32

NSCss (N+): number of stations with positive Nash Sutcliffe index (NS) values for the fitting to Css data; NSCss % (+): percentage of stations with positive Nash Sutcliffe Index (NS) values for the fitting to Css data.

Table 2 - Descriptive statistics of the R^2 and ERP statistical indices for the fitting of the rating curve model to the Css data, for the scenarios with complete data, 10-year periods and stream flow range for the stations analyzed.

Statistical indices	Complete data				10-year period				Flow range			
	Average	Min	Max	Stan Devi	Average	Min	Max	Stan Devi	Average	Min	Max	Stan Devi
R^2Css	0,19	7E-4	0,67	0,15	0,28	0,02	0,87	0,22	0,12	2E-5	0,83	0,16
ERPCss %	101	39	296	54	95	97	1939	154	89	19	473	65

R^2Css: values of the Coefficient of Determination applied to the Css data; ERPCss %: average percent relative error values, in %, applied to Css data.

The NSCss evaluation (Table 1) showed that, after the Css data was subdivided into 10-year periods, more stations had positive NS values, which would indicate that the fitting of the rating curve model had improvement.

Of the 58 stations with complete data, in total, after the division in the periods, 168 new subdivisions were obtained the NSCss statistics showed that, for 105 of these (62%), the applied rating curve model provides better estimates than applying the mean value (positive values). Previously, for the 58 with complete data, this NSCss behavior was identified in half of the stations (29 stations). However, the NSCss indicated only 32% positive when the datasets were subdivided into stream flow ranges.

When analyzing the ERPCss and R^2Css statistics for the Css data subdivided into 10-year periods, compared to the complete data, there is a small superiority in the model fitting. However, this perception of improvement is not as evident as expressed in the NSCss statistics. For R^2Css, the results were close, and considered low values, as results of the R^2 below 0.50 are a sign of inability of the rating curves to estimate sediments (Sadeghi et al., 2010).

From the results obtained when the Css dataset was subdivided into stream flow ranges considering the exceedance frequency ranges, it was found that only ERPCss showed a slight improvement in the average result. On the contrary, the results were worse for the other average statistics (R^2Css and NSCss). Thus, analyzing the average results of the statistical Indices, it is possible to state that the application of the rating curve to the data subdivided into stream flow ranges was the scenario that provided the worst accuracy in the estimate.

It should be emphasized that the statistical indices behave differently for each data set and different subdivisions. From this perspective, it is interesting to note the importance of using a set of statistical indices to evaluate a model applied to a data set. For a better evaluation of the statistical indices, Figure 3 depicts the related results for all the strategies, described in the form of boxplots and frequency distribution.

From the interpretation of Figure 3, the three statistical indices (R^2, ERP and NS) had a symmetrical behavior for strategy 1. Among the statistical indices, R^2 was more sensitive to the change of strategy, as it presented a greater variation of the results regarding the Css fitting. On the other hand, ERP showed greater stability to changes in strategies and less dispersion of data by the interquartile range, that is, smaller boxes, in comparison with the other statistical indices. In addition, the median positions demonstrate results close among the strategies.

However, another issue that can be discussed in the ERP results is the presence of more discrepant values, which indicate possible outliers. These higher values were observed in all the tested strategies. For the NS statistical index, the results showed greater data dispersion, i.e., greater variability, especially when considering the results for strategies 1 and 2.

With regard to the practical application of these results, the importance of using a set of statistical indices is highlighted when the objective is to evaluate the performance and behavior of a given model fitted to a data set. This was evidenced by the variation obtained among the applied statistical indices, whose sensitivity was different for each strategy of subdivision.

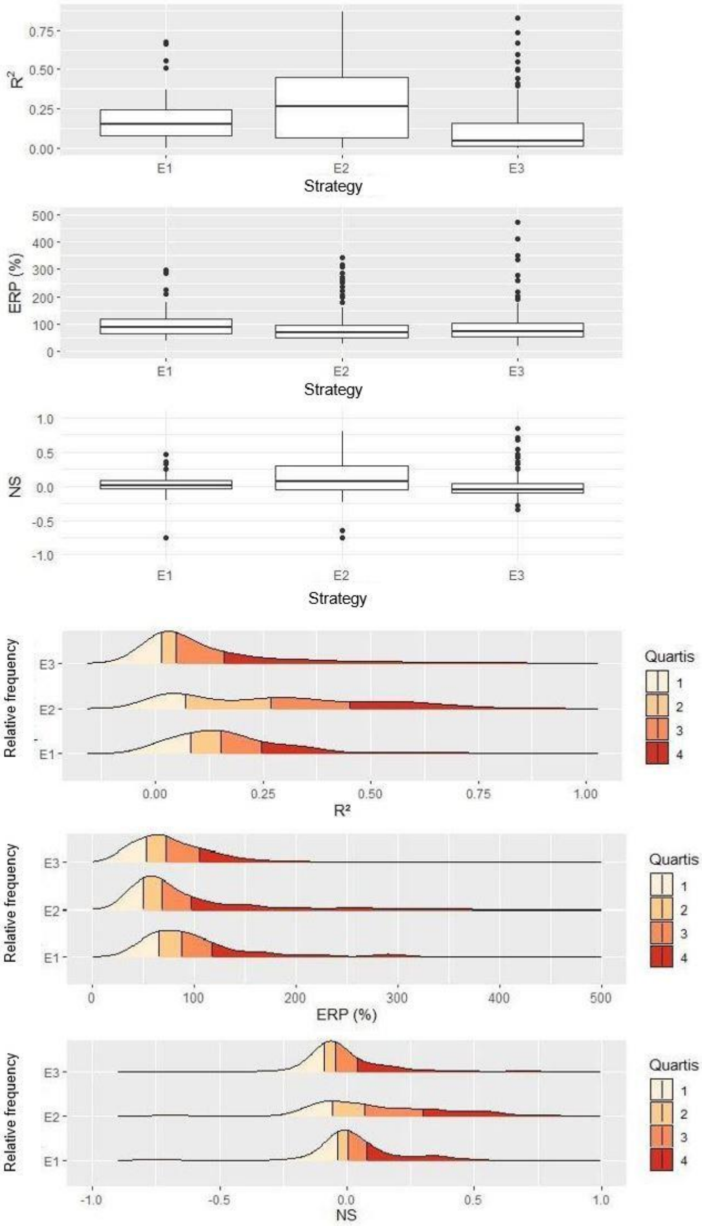

Figure 3. Boxplot and frequency distribution representing the results of R^2, ERP and NS, for the fitting of the sediment rating curve for the 3 analyzed strategies.

Rating curve fitting to Css data sets subdivided into 10-year periods

For some of the analyzed stations, as reported in the literature (HAPSARI, 2019), the subdivision of Css data set into 10-year periods resulted in $\overline{\text{ERPCss}}$ values lower than those obtained when using the complete data set (from up to 40 years), for which the highest $\overline{\text{ERPCss}}$ and the lowest $\overline{\text{R}^2\text{Css}}$ values were observed (Table 2). Asadi et al. (2021), based on the results, key curves without data separation had the lowest estimation power, while data separation significantly improved model performance. At station 77150000, for example, when the rating curve model was fitted to 10-year Css data periods, the ERPCss values were 76% and 51% for the period from 1998 to 2007 and 2008 to 2017, respectively; when its complete data set was used, the ERPCSS was 118%. Likewise, the use of the complete data set for station 74100000 provided ERPCss and R^2Css values of 114% and 0.17, respectively, whereas the statistical indices were 36% and 0.23, 68% and 0.47, and 53% and 0.55, respectively, when they were assessed for three periods (1978 to 1985, 1998 to 2007, and 2008 to 2017). This occurs because, when dividing a group of extensive data, several possible interferences and changes that may occur in the environment are minimized, reducing the ERP, increasing the R^2 and the quality of the fitting. These changes can generate modifications in the observed Css values for the same Q value; this behavior was identified in some stations.

Possible changes in land use in the watershed can be discussed in this sense due to their considerable influence on the behavior of erosion and sediment transport, thus affecting the relationships between Q and CSS (Hapsari, 2019). Conservationist practices, associated with proper soil use and management, for example, when implemented in watersheds, can reduce the effects of surface runoff, soil erosion and 75% of sediment yield (Yaekob et al., 2020). When using complete data sets, these changes may not be detected, as long-term data sets are used (e.g. 40 years of hydrological campaigns). However, when using series subdivided in 10-year periods or even for stream flow ranges, this effect can be reduced and, therefore, the fitting may be improved. It is worth noting that, even though the Mann-Kendall test for detecting trends has been used, it was applied to the annual average stream flow series as the Css data from hydrological campaigns are derived from few samples taken per year and cannot be therefore considered historical series.

Another applicability of data set subdivision is the ease in identifying periods where there would be possible errors in the measurements. This can be easily verified in the data set corresponding to the station 74100000 in which the subdivision presented, in general, an improvement in the efficiency of the model fitting. Nevertheless, the first period (1978 – 1985) resulted in an improvement more subtle that the others. These periods whose fits were poor may be eliminated from the modeling, thereby increasing the reliability of the Css value for a given Q. However, a point to be considered in the subdivision of the data set is that, after the subdivision, the values are smaller than when using the complete data. This results in a smaller amplitude of the stream flows considered and, consequently, tends to greater uncertainties for the extrapolation of values, which may generate greater discrepancies in the estimate of Css using the rating curve (Iadanza; Napolitano, 2006).

The improvement in the fit of the rating curve model applying data subdivided into 10-year periods was verified by Zhang et al. (2012). These authors applied the rating curve model to data sets from three sedimentometric stations for the Pearl River basin in China, splitting 50 years of data into different decades (1950s, 1960s, 1970s, 1980s, 1990s, and 2000s). Zhang et al. (2012) identified that the lower reliability of the estimated Css values of the rating curves and the lower model efficiency occurred when the model was applied to the complete data. The authors observed that the efficiency of the rating curve model might be increased when the Css data is subdivided, observed mainly by the NSCss results. In this way, when the data sets were subdivided into periods shorter than the complete period, a better efficiency was possible in the use of the rating curve model in one or more periods of the series, not ruling out the use of this model for that given station, as when it presented low efficiency for using the complete data set.

Another noticeable characteristic is that, for the vast majority of stations, the low efficiency of the model fitting occurs in the initial years of measurement, mainly those that had their measurements started from the 1970s onwards. Otherwise, for stations 72300000, 75500000, 85740000, the model proved to be an unfeasible tool for the three strategies associated with the use of data sets, presenting a low relationship between the data. For these stations, the R^2Css is among the lowest observed. This was also discussed and reported by Zeng et al. (2018) who applied the rating curve model to the complete data set and also evaluated traditional subdivision methods (seasonal and hydrological groupings, for example). Zeng et al. (2018) stated that the model was inappropriate and needed to be improved to be used for estimating Css in the Yarlung Zangbo river basin, in Asia. The authors attributed this inadequacy to possible interferences related to the characteristics of the climate, topography and relief of the region.

In this regard, two points can be discussed: i) the gain in information that is obtained when the Css data sets are subdivided into shorter periods as likely non-conformity of Css data sets can be easily identified, not completely affecting the application of the model to the data set; and ii) it was noticeable that in the measurements that started in the 70s, the Css data did not show good consistency for most of the stations analyzed; in other words, this period should be disregarded and the rest of the periods for future analyses should be used.

Fitting the rating curve to CSS data sets subdivided into stream flow ranges

Analyzing the average results of the statistical indices, it is possible to state that, among all the tested strategies, the application of the rating curve to the data subdivided into stream flow ranges provided the worst inaccuracies in the estimation of Css. These results go against the findings of some studies in the literature such as Tilahun et al. (2023) showed with their results that pooled annual datasets lead to unsatisfactory sediment classification curves and large errors in sediment load estimation and that stratifying the data into three periods strongly improved the performance of sediment classification curves.

Asselman (2000), applied the sediment rating curve model as a power function for data sets from several locations along the Rhine River, northwest Europe, and its main tributaries, using different adaptation procedures and different forms of subdivision. The author verified that the efficiency of the rating curve model increased when the Css data was subdivided, mainly when divided by stream flow ranges (high and low stream flows).

Girolamo et al. (2015) evaluated the applicability of sediment rating curves, developed as a function of hydrological conditions: high, normal and low stream flows, to estimate Css in the Celone River, Italy. The authors verified that the proposed method proved to be effective to represent Css for high and normal stream flows, however, it was possible to observe that the method tended to underestimate Css for high stream flows. For the aforementioned research, it is interesting to note that Css was continuously monitored in addition to frequent Css samplings during flood events, for normal stream flows, as well as for low stream flows. On the other hand, the data available and used in the present study was originated from sparse sampling.

In this perspective, it is important to consider the particularity of the Css data set used in this study, which come from hydrological campaigns for sampling suspended sediments. Furthermore, such hydrological campaigns are carried out with low frequency (e.g. twice a year) in many stations. This fact was discussed in the methodology section, corresponding to the criterion for selecting the period of years for the subdivision (10 years). Although most stations contained from 30 to 40 years of Css records, the data sets made available by the ANA have Css results from a small number of hydrological campaigns carried out annually. To understand this dimension, the total amount of Css records for the 63 sedimentometric stations analyzed ranged from 7 to 92, with an average of 60 Css records.

This characteristic is more significant when the data set is subdivided. It is worth mentioning that the number of Css records for the stations analyzed in this work when the data set was subdivided into stream flow ranges was much lower (average of 21 records) compared to the number of records taken in the other division strategies used in this discussion. Asselman (2000) subdivided the Css data sets in different ways, also considering stream flow ranges, for the application of the rating curve; however, the author applied complete series made up of at least 5,000 records. Girolamo et al. (2015) used a complete data set of 210 records for the application of the rating curve in stream flow ranges.

After fitting the model, these researchers observed lower determination coefficients in the ranges that presented the least amount of data (63 records for average stream flow and 10 records for low stream flows). Hassan (2014) argues that the amount of data for applying the sediment rating curve model is a limitation, and that this can be overcome by obtaining more observed data. Likewise and Hapsari (2019) and Horowitz (2008) observed that the fitting efficiency strongly depends on the sampling frequency, which includes the amount of data available to develop the rating curve of suspended sediments, as the large variation in field data can be minimized by gathering more observed data.

For data subdivided into stream flow ranges, the quality of fit of the sediment rating curve model seems to be more sensitive in relation to the number of hydrological campaigns and amount of data, and may present worse results when subdivided in this way. However, the data sets of some stations, individually, showed improvement in the estimate when the data was subdivided into stream flow ranges, as is the case of station 70700000 (Passo do Socorro). In this case, it is worth noting that all these circumstances must be considered for each of the stations separately, as each one presents a different behavior in relation to the division strategies, as well as to the statistical indices used. In addition, other forms of data subdivision have been presented in the literature. Zeng et al. (2018) proposed new subdivision methods for the sediment rating curve, based on Css ranges, for a river from the Tibetan Plateau in Asia. The authors identified that, in comparison with the rating curve based on the complete series and the methods of seasonal subdivision and stream flow ranges, the proposed methods improved the estimation of the suspended sediment load, with higher R^2 and NS, smaller biases and errors of the mean square root.

Fitting the rating curve to full CSS data sets

For the full Css data sets, the stations that presented the lowest ERPCss were Cascata Burica Nova (74610000) (R^2Css=0.67), Porto Lucena (74800000) (R^2Css=0.66), Passo do Ricardo (88680000) (R^2Css=0.15), Linha Cascata (74750000) (R^2Css=0.18) and Sanga Funda Montante (88177000) (R^2Css=0.37), with 39%, 41%, 42%, 47% and 49%, respectively. For all these, according to the NSCss, the rating curve methodology proved to be a better estimate than the mean value of the Css (positive values), except for Linha Cascata (74750000) which presented the NSCss equal to -0.11.

The results found from ERPCss to the complete Css data sets, indicated that 21 stations had an ERPCss above 100% and $\overline{R^2Css}$ of 0.13, and 5 stations provided an ERPCss below 50% and $\overline{R^2Css}$ of 0.41. In this regard, Sadeghi et al. (2010) assessed different models of rating curves for the Khamesan Basin in Iran and considered that coefficients of determination (R^2) smaller than 50% are a sign of inability of the rating curves to estimate sediments. When ERPCss was taken into account, we observed that the assumed error for some stations can be considered high, indicating that the fitted model does not satisfactorily represent the variation of Css as a function of Q. Thus, it is recommended to use the smallest ERPCss possible for additional calculations, associating it with statistical values, such as NSCss and R^2Css, where the most consistent relationships are found.

Another notable observation in view of these results is that the R^2Css tends to slightly increase with the decrease in ERPCss. Sadeghi et al. (2008), when applying seventeen models to obtain the sediment rating curve (Css versus Q) for a basin in Japan, obtained values of ERP from 19 to 431% and of R^2 ranging from 0.10 to 0.90. The authors recognized, together with the statistical efficiency criteria, that the power function was the best model to describe this relationship for the basin, with values of ERP, R^2, Standard Error of Estimation and NS equal to 153%, 0.53, 0.70, 0.32, respectively.

Based on the NSCss for the complete Css data sets, it was possible to observe that 50% of the 58 sedimentometric stations indicated that the average value of the observed Css is a better estimate than those obtained by the model (negative NSCss values). For these stations, the ERPCss ranged from 47% (station 74750000 Linha Cascata, R^2Css=0.18) to 297% (station 74470000 Três Passos, R^2Css=0.05), with a $\overline{ERPCss}$ of 123%.

The R^2Css for the fitting of these data sets had a minimum value of 0.001 for station 77150000 Uruguaiana (ERPCss=118%) and a maximum of 0.33 for station 85730000 Passo Linha Do Rio (ERPCss=285%). In the remaining complete Css data sets (29), the NSCss statistic indicated that the model was a better estimate than the average Css value. For these, the ERPCss ranged from 39% (R^2Css=0.67) for station 74616000 Cascata Burica Nova, where this station presented the lowest ERPCss in the fitted values among all the stations, to 132% (R^2Css= 0.270) for station 85623000 São Sepé - Amount, with a value "ERPCss" of 80%. The R^2Css for the fitting of these data sets ranged from 0.13 for station 76560000 Manoel Viana (ERPCss=82%) to 0.67 for station 74610000 Cascata Burica – Nova (ERPCss=39%), with $\overline{R^2Css}$ of 0.28.

In general, one can observe that those stations in which the NSCss statistic presented negative values (indicating that the average Css value is a better estimate than the model values), the value of $\overline{ERPCss}$ was higher (123%) and $\overline{R^2Css}$ smaller (0.09) when compared to those for which the NSCss statistic showed positive values (indicating that the model is a better estimate than the mean value of the data), where $\overline{ERPCss}$ was

80% and $\overline{R^2Css}$ equal to 0.28. This demonstrates agreement among the statistical efficiency criteria applied.

When analyzing the data sets from the sedimentometric stations, the low relation in the values of several stations was verified. It should be mentioned that the same value or very close values of Q, observed on different dates, i.e., presented greatly discrepant values of Css, thereby not showing a good relationship. This peculiarity has an impact on the quality of the rating curve fittings and, therefore, on the results of the efficiency statistics, ERP, NS and R^2, obtained between the observed and estimated values by the rating curve (Asselman, 2000).

This particularity of distinction perceived in the Css data associated with Q is in line with what was reported by Schmidt and Morche (2006). These authors found from Css data sets in two small mountain basins in the Bavarian Alps in Germany that the correlation between Css and Q was generally poor. In this sense, recent studies such as Wang and Liu (2022) analyzed the degree of synergy between runoff and suspended sediment transport between 1958 and 2016, taking as an example the largest and most continuous region from the Huangfu River to the Jialu River on the plateau. of Loess. The authors observed that approximately 70% of flood events in the five river basins had low degrees of synergy between flow and sediment processes at the time of the flood.

In this aspect, some justifications can be used to substantiate this inequality in the measured values. The rating curves may not present a good fit due to the non-use of the same monitoring section in the watercourse, the change of equipment and technicians for measurements, errors associated with data processing, and changes in stream flows in periods different from monitoring (Carvalho, 2008). For the latter, which can be applied to the stations considered in this work, Zhang et al. (2012) suggest separating the stream flows of these periods, or dividing them into sections (periods of years, dry and wet periods, quarters, months, seasons of the year or periods of spring-summer and fall-winter), thus allowing the generation of individual rating curves.

Conclusions

The estimated Css values from the tested rating curve model showed improvement when the data sets were subdivided into 10-year period, indicating a viable adjustment from the point of view of applicability of the rating curves. For some of the stations, the following limitations were recognized: the reduced frequency of hydrological campaigns, the reliability and quality of the data, the relationship between Q and Css, and the need for extrapolation. Furthermore, changes in watershed characteristics as well as the effect of hysteresis may not be recognized and identified in the fitting.

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