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ENGINEERING SCIENCES

Stochastic simulation in reservoir sedimentation estimation: application in a PCH

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Abstract: In reservoir projects it is important to estimate when the accumulated sediments will start to interfere with their functions. However, predicting silting is difficult because the processes involved have some uncertainties. Thus, the study is not only deterministic, as currently performed, but also stochastic. Thus, the objective of this paper was to develop a stochastic method and evaluate its performance in estimating silting in reservoirs. The method has as originalities the fact of having coupled a deterministic model widely used in the area of Hydraulics to a stochastic one. Another originality was to validate the stochastic method developed from silting data obtained in the reduced model of a Small Hydroelectric Power Plant (SHP). Thus, it was observed that the real silting was always between the 1st and 3rd quartile of probability of the stochastic result. Thus, the main advantage of the stochastic model developed was to allow obtaining the probabilities of silted heights in the stretches of interest. In addition, the variability of the results in the simulations indicated the sections that may suffer greater silting. In this way, hydraulic structures can be better positioned. Preventive and corrective measures can also be better planned and executed.

Key words: HEC-RAS, numerical modeling, physical modeling, AR(1) model.

INTRODUCTION

When a reservoir is built, whether for public water supply, power generation or other purposes, changes may occur in the physical and hydraulic characteristics of the watercourse in which the structure was built. The increase in the wetted area of the river's cross section and the decrease in the waterline slope causes a reduction in the flow's speed and turbulence. Such reductions have the effect of slowing the movement of particles in the stream direction (Habets et al. 2018) and of restricting the resultant of sustaining forces. In this way, solid particles can be deposited throughout the reservoir (Mamede et al. 2018). Therefore, the reservoirs are subject to some degree of sedimentation. The consequences of this can be numerous such as, for example, reducing the lifespan of the reservoir (Braga et al. 2019), affecting dam safety and promoting ecological impacts, since fine suspended sediments represent an important source of adsorbed nutrients (Maavara et al. 2015), thus accelerating the eutrophication process.

In the case of hydroelectric reservoirs, siltation is a serious problem that leads to a decrease in the power generation capacity of the plants, since there is a change in the regularized flow. Thus, the concessionaire's revenue from the sale of electricity is reduced, which consequently will result in the reduction of the financial compensation that is paid to the States, Municipalities and Government Agencies, revenue which is proportional to the electricity generation.

Considering the problems that can be caused by siltation, studies aiming to present methodologies to predict sedimentation rates in reservoirs are essential. These studies are important both in the design phase and throughout the reservoir operation, since it is necessary to estimate when silting will start to interfere with the functions for which the reservoir was built. The economic viability of a dam project may also depend on this silting estimation. Furthermore, both preventive and corrective measures can be made in a more efficient manner, since as discussed by Adam et al. (2015) and Schleiss et al. (2016), the study of sedimentation in reservoirs should be a priority for the decades to come.

It turns out those estimating sediments accumulation is a difficult task because the processes involved – erosion, transport, deposition and consolidation – are complex and can occur simultaneously. In addition, the factors that interfere in the process are subject to great temporal variability, which is difficult to control (Kuria & Vogel 2015). They are also subject to various uncertainties such as those related to the model, which usually stems from an incomplete understanding of the system being modeled, as well as uncertainties related to the data.

In order to obtain reliable results, representative and consistent local data are also necessary. However, this data is rarely available, since the density of sedimentometric stations is reduced, long-term sampling in places of interest is uncommon and there is often no public access to the data. In addition, in the existing station, only measurements of the concentration of suspended solid are made, without determining the total solid discharge and granulometry data. For this reason, many sedimentological studies in the country are hampered.

Thus, estimating the silting process only from a deterministic point of view, as it is currently done, causes all uncertainties associated with the process to be neglected. This can lead to erroneous results of silted heights, since a deterministic model provides a single siltation result for the analyzed period. Thus, using only deterministic modeling in reservoir projects can overestimate the structure lifespan, as noted by some authors.

Thakkar & Bhattacharyya (2006) pointed that 14 out of the 27 reservoirs studied in India present an annual siltation rate higher than the foreseen in the viability studies. The authors argue that a reason for this to occur is the deficiency and limitation of the data used, so that there is great uncertainty in the siltation forecasting studies, and that this can lead to serious management problems in water and energy security. For the other 13 reservoirs, there was no comparison between the annual silting rate and the project rate, as the authors did not obtain the project data.

Ribeiro & Salomão (2001) cited that the Small Hydroelectric Plant (SHP) Casca I was deactivated earlier than expected and the Hydroelectric Power Plants (HPP) Casca II and Casca III had reduced generation compared to the project due to the high sediment concentration in its reservoirs. Another case that presented early siltation problems was the Itiquira HPP, in which the reservoir lifespan was reduced by seven years, due to silting (Carvalho et al. 2000).

Miranda (2011) carried out simulations of the regularization capacity of the Três Irmãos HPP reservoir after its siltation. He verified that during the dry season the reservoir could not fully meet its project demands, failing to generate an average of 377 MWh per month during the 15 years of the studied period.

In view of the above, it can be noted that stochastic modeling is a promising tool for estimating siltation in reservoirs, since it considers the uncertainties involved in the process. In addition, when using this approach, the final products of the simulation are thousands of siltation scenarios. Thus, the statistics of the deposited sediments in the reservoir over time can be determined, such as: the median; the standard deviation; and the probability of a cross-section and/or longitudinal profile have bigger or smaller silted height.

Therefore, the study of silting must be approached not only in a deterministic way, but also in a stochastic one, as proposed by Guo et al. (2018), Shrestha et al. (2016), Schleiss et al. (2016), Estigoni (2016), Câmara et al. (2016), Adam et al. (2015), Oh et al. (2015). Hager (2018), in his state of the art, also states that, despite the countless works already carried out in the area, the study on the best methodology to be used in estimating siltation remains important.

However, it is noteworthy that none of the cited works developed what is proposed here. One originality of this paper consists in the fact that it has coupled a deterministic model widely used in the hydraulic area, which is HEC-RAS, to a stochastic model. The latter was developed in the software R (widely used in Statistics), so that thousands of silting simulations could be automatically carried out.

Another originality of this paper was to validate the stochastic method developed from the siltation data obtained in a reduced model of a SHP. The use of this physical model allowed for greater precision in the use of hydrosedimentological data and the simulation of silting scenarios. Furthermore, it facilitated the inspection of the siltation process during the analyzed periods.

Therefore, this paper's main contribution is to associate three types of siltation modeling: stochastic, deterministic and physical. Thus, the objective of this paper was to promote the coupling of a stochastic model to a deterministic one, in order to develop a method for stochastic estimation of silting in reservoirs. Furthermore, the stochastic method performance was evaluated in order to observe whether the silting results obtained from the numerical stochastic simulations covered the real scenario observed in the reduced model.

MATERIALS AND METHODS

Overall presentation of the methodology

To carry out this work, the hydrosedimentological and topographic data were used. The data is from a SHP, which was built in 1956 and is currently inoperative, since its reservoir is intensely silted. This SHP was chosen because there was a reduced model of its reservoir, and the results obtained in this physical model were used to validate the developed stochastic method. The methodology is divided into three parts, as shown in Figure 1, namely: (i) stochastic modeling; (ii) coupling the stochastic to the deterministic model; and (iii) physical modeling. These steps are interconnected to achieve the objective of developing a stochastic method, which aims at estimating siltation in water reservoirs and the probability of its occurrence.

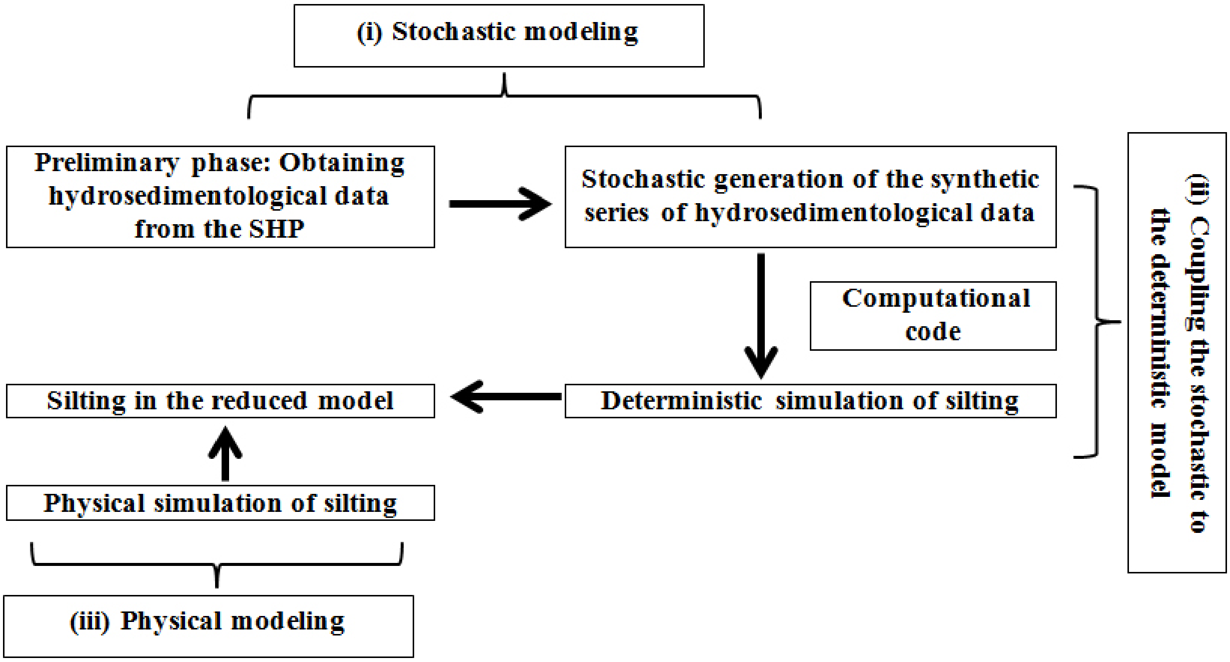

Figure 1. Methodology flowchart.

Stochastic modeling

Obtaining hydrosedimentological data

The water and sediment related parameters are essential to the study of siltation. To stochastically simulate the hydrosedimentological data, the following parameters were considered of interest: (i) average annual flow affluent to the reservoir, called annual flow (Q); and (ii) average annual total solid discharge (Q_{ST}). These parameters were considered stochastic, as they have space-time variability in addition to uncertainties in their values, due to their measurement methods and other factors. Other parameters could be considered stochastic, such as the sediment specific weight, the Manning roughness coefficient and the sediment particle size. However, they were not stochastically simulated, because in the reduced model, also used in this work, their variation was not possible.

In order to determine the two stochastic parameters, the SHP administration granted access to the data on daily flows and total solid discharges from measurement campaigns. With the historical series in hand, the data was preliminarily analyzed in order to observe inconsistencies and/or discontinuities. Subsequently, from the daily flows, the "Q" of each hydrological year was obtained. The hydrological year was considered between October of one year and September of the following year, based on the observation of the historical series. The second stochastic parameter, "Q_{ST}", was obtained from the SHP sediment rating curve. From the hydraulic similarity, the SHP data was converted to the scale of the reduced model. The "Q" are shown in Figure 2 and the "Q_{ST}", represented in the sediment rating curve, are in Figure 3.

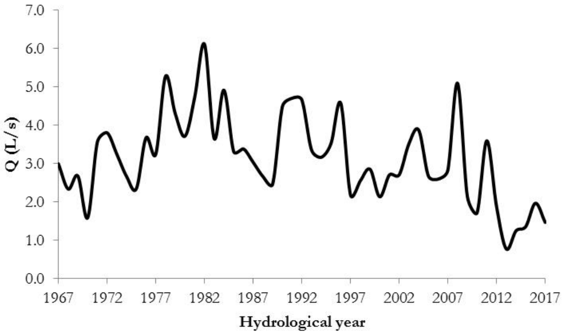

Figure 2. Annual flow series of the reduced model of the SHP.

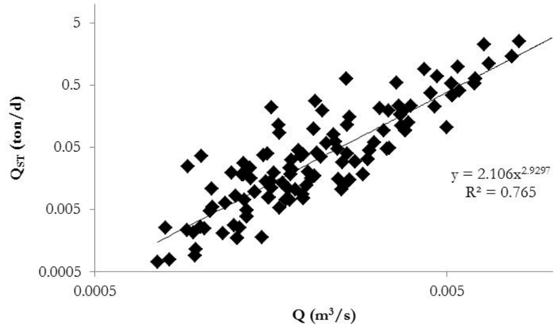

Figure 3. Sediment rating curve of the reduced model of the SHP.

Stochastic generation of synthetic series of hydrosedimentological data

As shown previously, the parameters considered stochastic in this work were: affluent annual flow (Q) and average annual total solid discharge (Q_{ST}). First, the "Q" synthetic series were generated and, from them, the "Q_{ST}" series were generated.

For many environmental processes it is likely that the state at a given time is correlated with the state at earlier times. These processes are referred to as autoregressive processes, AR. In an autoregressive process, the present value of the time series is expressed linearly in terms of the past values of the series and the random perturbation occurring at an instant. Thus, the "Q" synthetic series were generated based on the SHP's historical series of flows and using the AR(1) autoregressive stochastic model, presented in Equation 1. Box and Jenkins (1970) popularized the use of this type of model.

$$Q_t = \overline{Q} + \phi(Q_{t-1} - \overline{Q}) + \sigma_x \epsilon_t \sqrt{1 - \phi_1^2} \tag{1}$$

Where,

Q_t is the annual flow for the time t of interest, in "m^3/s";

$\overline{Q}$ is the average of the observed data of the temporal series of the SHP's flows, in "m^3/s";

ϕ is the lag 1 autocorrelation coefficient of the temporal series of the SHP's flows;

σ_x is the standard deviation of the temporal series of the SHP's flows;

ϵ_t is the randomness component generated from the Normal distribution N(0,1). It is the stochastic component of the AR(1) model. According to Chatfield (2000), it is a stationary, independent (no autocorrelation), normally distributed (white noise) random variable.

According to Chatfield (2000), one of the premises for using the AR(1) stochastic model is that data need to be stationary. For this reason, the stationarity of the "Q" series of the SHP was verified using Spearman's nonparametric test, as recommended in Naghettini & Pinto (2007). The test was applied using the statistical software R, at a significance level of 5%. As each statistical test has its power, that is, it may not reject the null hypothesis if it is false, in order to reinforce the Spearman test response, the stationarity of the "Q" data was also tested by the Mann-Kendall test, presented in Naghettini & Pinto (2007). For this, the Trend software was used, at a significance level of 5%.

Another premise that was observed for the use of the AR(1) model is whether the data followed a normal distribution. Thus, in possession of the “Q” series of the SHP, in the statistical software R, the Shapiro-Wilk test was applied, at a significance level of 5%.

Observing Equation 1, it can be noted that the parameters of the stochastic model are the mean, the standard deviation and the lag 1 autocorrelation coefficient of the “Q” series. These parameters were obtained in the R software, and to verify the autocorrelations of the data, a correlogram was constructed, from which the value of the lag 1 autocorrelation coefficient was obtained.

After the premises of the stochastic model were tested and its parameters obtained, 1000 synthetic series of “Q” were generated in R, starting from Equation 1. For these series, their statistics were verified (mean, variance and lag 1 autocorrelation). These values were compared to the “Q” historical series of the SHP, in order to verify if the AR(1) model adjusted well to the original data. It is noteworthy that 1000 series were generated, because for that quantity the statistics of the generated data converged to those of the original series, as will be presented in the Results item.

Another analysis performed to observe the adjustment of the AR(1) model to the data was based on the residues (ϵ_t) of the synthetic series. For this, Equation 2 was used in the R software.

$$\epsilon_t = X_t - Y_t \tag{2}$$

Where,

X_t is the flow value of the synthetic series in the year t;

Y_t is the value corresponding to the same year in the original series.

For each “Q” generated by the AR(1) model, the respective “Q_{ST}” value was generated, using the sediment rating curve (Figure 3). However, as the stochastic parameters have a degree of uncertainty and randomness, it was not admitted that the relation between them was univocal. Thus, each “Q_{ST}” value was generated from a Normal distribution, which average was equal to the total solid discharge found by the regression equation, for a value of “Q”, and the standard deviation was fixed and equal to the standard deviation value of the regression residues, which is 0.006 t/d. For example, using the AR(1) stochastic model, a “Q” of 0.0064 m^3/s was generated.

When entering this value in the sediment rating curve equation (Figure 3), a total solid discharge of, approximately, 0.74 t/d was found. In the R software, a “Q_{ST}” was randomly generated, following a Normal distribution, which average was 0.74 t/d and the standard deviation was 0.006 t/d. Thus, for each annual flow generated stochastically, the respective “Q_{ST}” was drawn. Thus, as 1000 synthetic “Q” series were generated, 1000 “Q_{ST}” series were also generated.

However, Teixeira et al. (2020) observed, in the same reduced model used for this article, that annual flows (Q) did not move the sediment. Thus, Teixeira et al. (2020) proposed that the flow responsible for causing siltation in the SHP, for the period from 2013 to 2017, were the average of the waves that contained the maximum flows (Q_{MM}). Thereby, it was necessary to generate synthetic series of “Q_{MM}”.

For the historical series of the SHP’s daily flows, all average flows of the flood waves (Q_{MM}) were stipulated. The values of ”Q_{MM}” were divided by ”Q”, that is, it was observed how much the average of the flood waves were higher than the annual flows. Figure 4 shows the relation between the “Q”, already converted to the reduced model, and the Q_{MM}/Q ratio, which is called K.

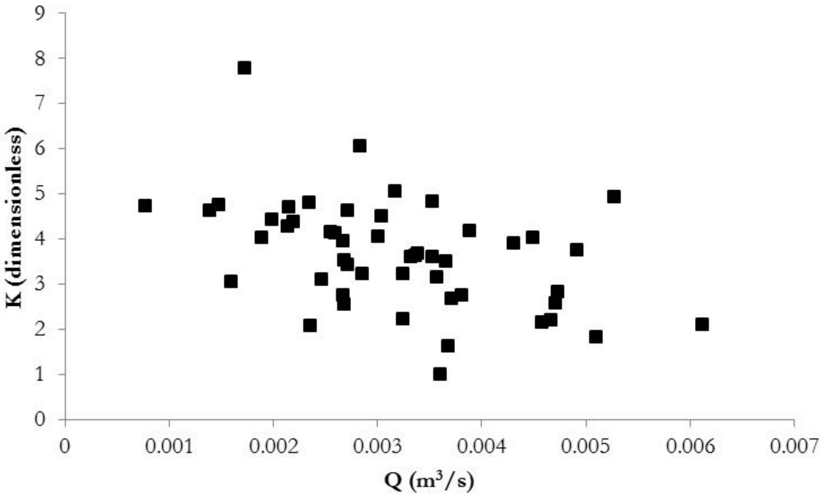

Figure 4. Relation between annual flows (Q) and K values, referring to the physical model.

From Figure 4, it can be noted that the relation between these variables is random. Then, to obtain the “Q_{MM}” from the “Q” that was generated stochastically, the following procedure was used: the “Q” was generated from the AR(1) model; they were then multiplied by “K” values, where “K” was randomly obtained from a Normal distribution, of which mean and standard deviation refer to the values in Figure 4.

It is noteworthy that, in R, the Shapiro-Wilk test was applied to the “K” values series, at the level of significance of 5%, to identify whether they followed the normal distribution of probably, which was confirmed by test. The following tests presented in Naghettini & Pinto (2007) were also applied at 5% significance: the number of inflections test proposed by NERC, to verify the randomness of the data; the independence test recommended by Wald and Wolfowitz; the Mann and Whitney homogeneity test; and the Spearman test for stationarity.

Summarizing this stage of the work:

- After verifying the premises of the AR(1) model, 1000 series containing the annual flows (Q) were generated;
- To generate the 1000 series of the average flows of the maximum periods (Q_{MM}), all the “Q” generated were multiplied by “K” values, which were generated randomly from a Normal distribution;
- From the 1000 series of “Q” and in possession of the sediment rating curve, the total solid discharge values were generated, which served as parameters for the Normal distribution, and from this distribution the series of total solid discharges (Q_{ST}) were generated referring to the “Q” series.

At the end of the stochastic generation, the 1000 series of average flows of the maximum flow period (Q_{MM}); 1000 series of annual flows (Q); and equal number of series of total solid discharges (Q_{ST}) were generated. All series values were converted to the reduced model. The series had values for the period comprehended between 1967 and 2017.

Deterministic modeling coupled with stochastic modeling

The stochastically generated series of “Q”, “Q_{MM}” and “Q_{ST}”, were introduced in a deterministic mathematical model, which has hydrodynamic and sediment transport equations. The HEC-RAS 5.0.3 software was used in this work due to its consolidated application in this area, as can be seen in the works of Teixeira et al. (2020) and Gibson et al. (2017).

The HEC-RAS software solves the hydraulic equations in steady state. However, it allows you to discretize the input hydrograph in time intervals as small as you want to define. Thus, the waterline and sediment transport calculations in a transient regime can be considered as almost non-permanent. When starting the mathematical modeling, the software performs the waterline calculation through energy conservation equations. They are solved by the standard step method. The pressure drop is calculated by the Manning’s equation. The basis for simulating the vertical movement of the bed is the sediment continuity equation – Exner’s equation. The program solves the equation by the finite difference method.

When working with mathematical models, it is necessary to choose the most suitable formulation for the transport of the solid carrier material and the bed. According to USACE (2016), the equations incorporated by the HEC-RAS software are: Ackers & White (1973), Engelund & Hansen (1967), Laursen (1958), Meyer-Peter & Muller (1948) , Toffaleti (1968), Yang (1973, 1984) and Wilcock & Crowe (2003). All these formulations can be found in the program manual. The equation used in this research was that of Wilcock & Crowe (2003). It was the one that best adjusted to the hydrosedimentological data used.

The HEC-RAS controller automatically read and input into HEC-RAS 5.0.3 the 1st series containing “Q”, the 1st series of “Q_{MM}” and the 1st series with “Q_{ST}”. After inserting these data, the first siltation result for the reduced model of the SHP reservoir was generated in HEC-RAS 5.0.3. The controller performed this procedure another 999 times, since 1000 series were generated for each stochastic parameter. Thus, in the end, for the period from 1967 to 2017, 1000 silting results were obtained for the reduced model of the reservoir.

As will be explained in the Physical Modeling topic, for the reduced model of the SHP, siltation was known for two periods: 2008 to 2012 and 2013 to 2017. It happens that HEC-RAS allows silting to be observed for periods. Thus, 1000 results were simulated for the period 1967 to 2017, but with the HEC-RAS controller, only the results for 2008 to 2012 and those for 2013 to 2017 were extracted. Therefore, each of the two periods had 1000 silting results. For these results, its statistics were determined, such as: the mean, median, standard deviation and the probabilities of certain siltation heights to occur along the reduced model of the SHP reservoir.

Physical modeling

The reduced model used in this research was built to study the silting of the SHP, which is the area of study of this paper. More details on the reduced model can be found in Carvalho et al. (2014). The authors stated that the hydraulic similarity principles were used to dimension the model. These principles involve obtaining similarities in dynamic, geometric and kinematic scales. The equations used in the design of the model can be obtained from Julien (2002). In Table I, Obtained in Teixeira et al. (2020), shows some scales of the reduced model.

Table I. **Proposed scales in the design of the reduced SHP model.**

Quantities	Scale	Real Value	Model Value
Length	99.3	1200 m	12.1 m
Width	99.3	600 m	6.0 m
Depth	25.0	30 m	1.2 m
Grain Diameter	0.4	0.45 mm	1.13 mm
Time	2,483	5 years	17.6 h
Froude Number	1	-	-
Reynolds Number	125	-	-
Sedimentation rate	2.5	7.9 cm/s	3.1 cm/s
Sediments Density	15.8	2.65	1.11

Table II. **Data used to simulate the siltation occurred between 2008 and 2012.**

Year	Q_{MM} (m^3/h)	Q_{ST} (t/d)
2008	34.5	0.017
2009	38.1	0.026
2010	33.1	0.037
2011	32.9	0.016
2012	33.5	0.031h

Teixeira et al. (2020) evaluated the efficiency of the same reduced model used in this work. The authors concluded that this model was able to simulate the siltation between 2013 and 2017 at the SHP. In addition, these authors proposed a silting simulation methodology in physical models.

Using the hydrosedimentological data of the SHP, the methodology proposed by Teixeira et al. (2020) was applied and the siltation simulated in the reduced model of the SHP, for the period of 2008 to 2012. The procedure developed by Teixeira et al. (2020) suggested the use of the average flow rates of the maximum periods (Q_{MM}) and the total annual solid discharges (Q_{ST}). Each "Q" and "Q_{ST}" pair should flow for 30 minutes, for each year. Thus, the total flow time was 2.5 h, for the simulation of silting in the five-year interval (2008 to 2012). Table II show the values used in the operational procedure.

All the procedure details for the physical simulation of silting can be found in Teixeira et al. (2020), and will not be presented here, as the assessment of physical modeling is not part of the objective of this article.

At the end of 2.5 h, the deposit measurement was made with the aid of a photoelectric sensor. To compose the longitudinal profile of the silting, the measurement was made at the cross sections point with the lowest level, which is the same procedure used by HEC-RAS 5.0.3. The silting result for the period of 2008 to 2012, obtained in this work, and the silting that occurred between 2013 and 2017, obtained by Teixeira et al. (2020), was compared with the silting obtained via stochastic simulation, to validate the developed stochastic method that was described previously.

Methodology summary

Initially, the series of average annual flows (Q) and total annual solid discharges (Q_{ST}) for the SHP were obtained, and these series were converted to the reduced model, using hydraulic similarity scales. Subsequently, using the AR(1) stochastic model, 1000 synthetic series of "Q" for the period comprehended of 1967 to 2017 were generated. From these series, 1000 series containing the average flows of the maximum periods (Q_{MM}) and 1000 series of "Q_{ST}" were generated.

All the “Q”, “Q_{MM}” and “Q_{ST}” synthetic series were automatically input, one at a time, into HEC-RAS 5.0.3, which simulated siltation in the SHP reduced model. At the end, 1000 results of silting for the period between 1967 and 2017 were obtained, being that 1000 results were extracted for the period 2008 to 2012 and another 1000 for the period 2013 to 2017.

Aiming at validating the developed stochastic method, the statistics of the siltation results obtained via the stochastic method were compared with the siltation results observed in the SHP reduced model. It is noteworthy that in the physical model the result was available for two periods: 2008 to 2012, which was obtained by the authors of this article, and the period from 2013 to 2017, obtained by Teixeira et al. (2020).

RESULTS AND DISCUSSION

Stochastic modeling: Generation of synthetic series of hydrosedimentological data

The AR(1) stochastic model premises were tested before the model was used. One of them is that the series of data should be stationary. When applying the Spearman and Mann-Kendall non-parametric tests, both at 5% of significance level, it was found that in the historical series of annual flows (Q) there is no temporal trend. Another premise is that the data should follow a Normal distribution. Based on the Shapiro-Wilk test, at 5% of significance level, it was obtained that the sample comes from a Normal population.

In order to verify the “Q” series autocorrelations of the SHP, its correlogram (Figure 5) and its partial autocorrelation function (PACF) were made (Figure 6). The result showed a significant autocorrelation of approximately 0.35 for Lag 1, which is the only significant correlation, according to the confidence interval (dashed blue line in Figure 5). According to Chatfield (2000), in the case of AR models, if the series is stationary the correlogram quickly falls to the autocorrelation limits equal to zero, as occurred. In the PACF graph (Figure 6) there is a significant correlation in Lag 1 followed by correlations that are not significant. According to Chatfield (2000), this pattern indicates an autoregressive model of order 1.

Since the premises of stationarity and normality were met, 1000 synthetic “Q” series of the SHP were generated following the process presented in Equation 1, which guarantees through its random term, that all series are different. In possession of the synthetic series, its main statistics were analyzed in order to compare them to those of the original series. The results are shown in Table III, and for the synthetic series they are resultant of all 1000 series.

Table III. Main statistical parameters of the original and the synthetic series.

Parameter	Original series	Synthetic series		
		Lower limit	Average	Upper limit
Flow (m^3/s)	40.68	37.30	40.67	44.01
Standard deviation (m^3/s)	13.15	10.78	12.98	14.87
Autocorrelation	0.35	-0.01	0.30	0.45

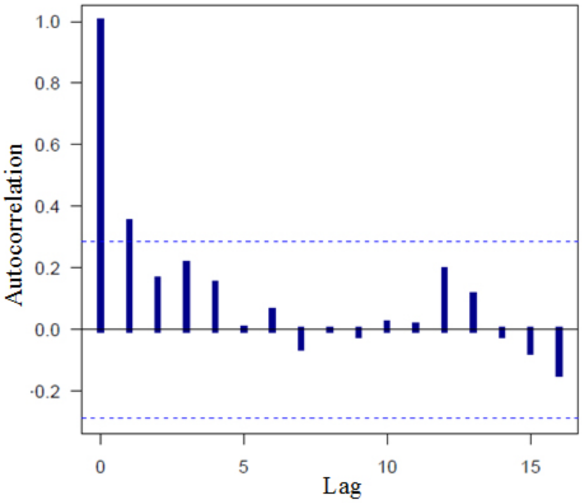

Figure 5. Annual flows correlogram of the Salto do Paraopeba SHP (1967 to 2017).

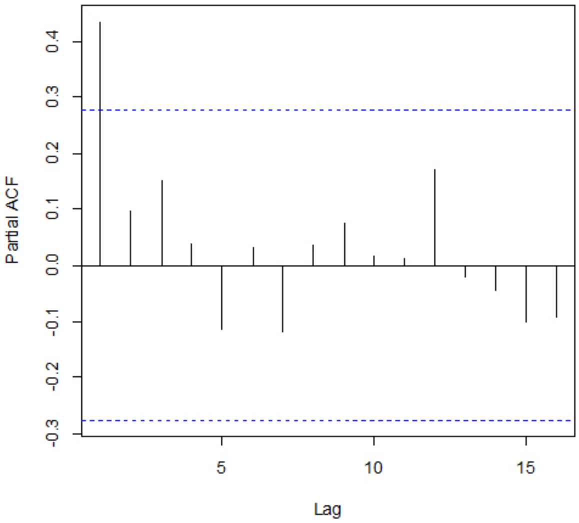

Figure 6. Partial autocorrelation function of the annual flows of the SHP (1967 to 2017).

As seen in Table III, there was little average variation between the historical series and the statistical parameters of the synthetic series, which suggests that the average of the generated data in relation to each analyzed item can be considered constant. The autocorrelation variation was greater, which is due to the random portion of the AR(1) model. However, the 0.30 autocorrelation of the synthetic series remains significant, since it is still above the 0.28 limit (verified limit so that the autocorrelation is significant – Figure 5).

The average and the autocorrelation of the residues (et) of the 1000 synthetic series were also analyzed. The results are shown in Table IV. The “Q” residues of the synthetic series, with an average value of almost zero, indicate that the AR(1) model adjusted well to the data, according to Chatfield (2000), disregarding the dimension of its values.

Table IV. Main statistical parameters of the synthetic series residues.

Parameter	ϵ_t
Flow (m^3/s)	-0.006
Autocorrelation	0.319

Since it was verified that the AR(1) model adjusted well to the data, each “Q” value of the 1000 series generated for the SHP was multiplied by the “K” factor, which was obtained randomly from a Normal distribution, as explained in the methodology . This was necessary to convert the annual flows (Q) to average flows of the maximum periods (Q_{MM}), since it is these flows that causes sediment transport in the SHP reservoir, as observed by Teixeira et al. (2020). It should be noted that the statistical tests applied, at 5% significance, showed that the data set containing the “K” factor (Figure 4) is homogeneous, independent, random and stationary. Although they do not cause sediment transport, the “Q” were useful to generate the total solid discharges (Q_{ST}), which provided the amount of sediment accumulated in the reduced model close to that of the prototype. Thus, at the end of the stochastic generation, 1000 series containing the average flows of the maximum periods (Q_{MM}), 1000 containing the annual flows (Q) and another 1000 with the total solid discharges (Q_{ST}) referring to the annual flows were obtained.

Physical modeling of the siltation

In order to validate the developed stochastic method, the siltation period (2008 to 2012) was simulated in the reduced model. The entire simulation procedure was carried out according to Teixeira et al. (2020). The silting of the period in question is shown in Figure 7, while the longitudinal profile of this silting is shown in Figure 8.

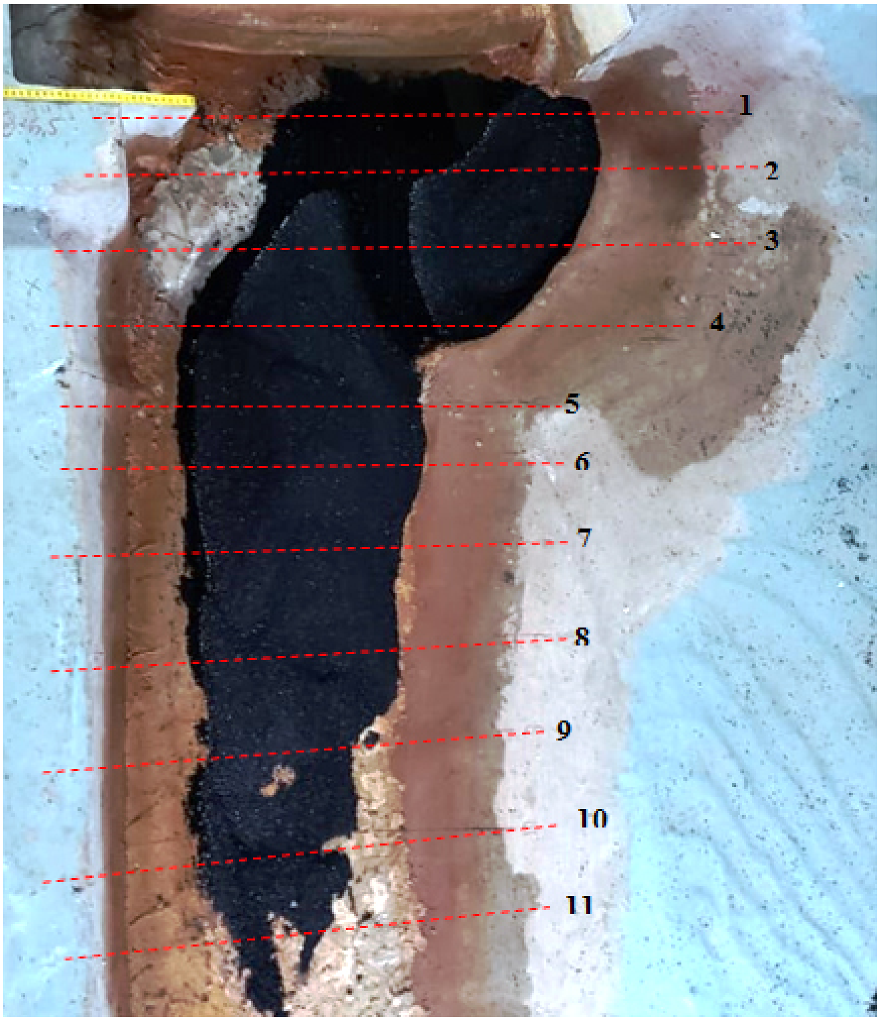

Figure 7. Siltation obtained in the reduced model of the SHP, for the period between 2008 and 2012.

It can be observed from Figure 7 that siltation took place between sections “1” and “11”. However, in this last section, the sediment layer was very thin and that layer was not at the measurement site, which was the lowest point of the cross section. Therefore, it can be seen in Figure 8 that the measured sediment deposits occurred in the last ten cross sections (sections “1” to “10”), as well as in

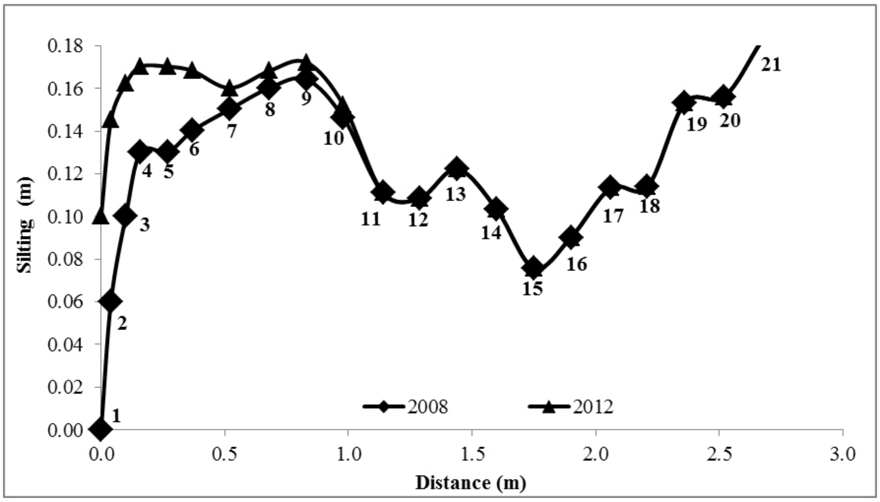

Figure 8. Longitudinal profile of the siltation observed in the reduced model, for the years 2008 and 2012.

the 2013-2017 period, observed by Teixeira et al. (2020). Moran et al. (2013) also obtained good silting results using physical models.

Siltation obtained via the stochastic method: Coupling the deterministic and stochastic models

Figure 9 presents the dispersion of the results of the 1000 simulations of silting, in which the central lines in the rectangles represent the median value of siltation, whereas the lower and upper limits in each rectangle represent, respectively, the 1st and 3rd quartiles. The 1st quartile refers to 25% and the 3rd one refers to 75%. The siltation values correspond to the elevations in relation to the bottom of each cross section. Also shown is the siltation of the reservoir in the reduced model in the year 2017.

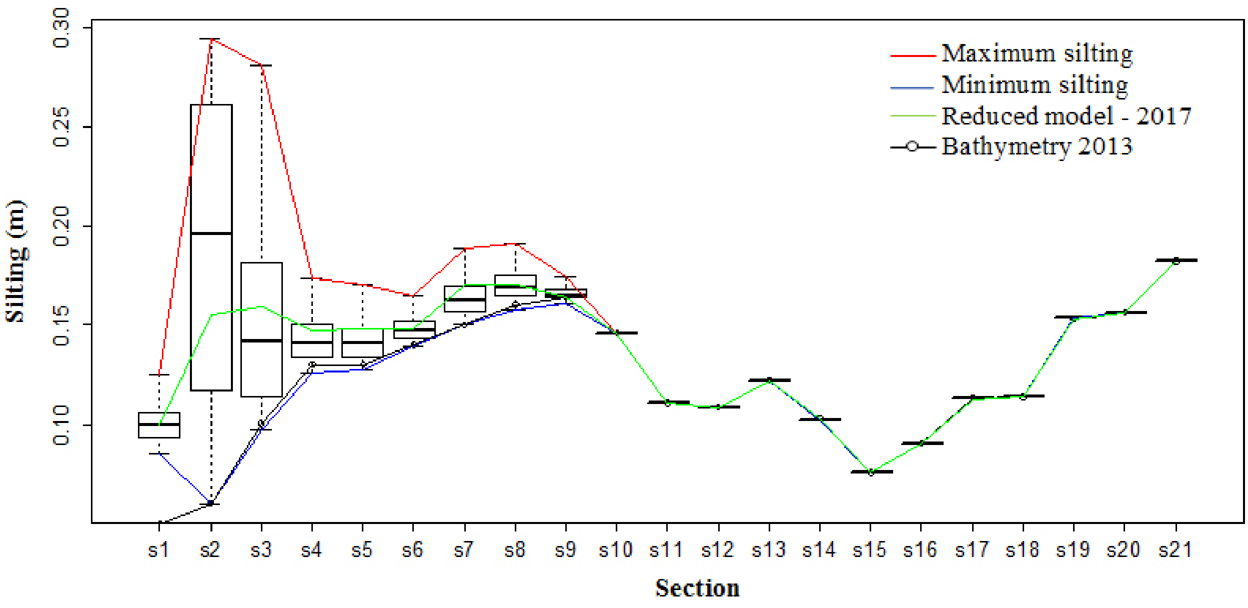

Figure 9. Result of the stochastic simulation for siltation occurred between 2013 and 2017, in the 21 cross sections, and the bathymetry of 2013 and 2017.

Figure 9 shows that the stochastic method represented well the sections where silting occurred. Like the bathymetry of 2017, siltation via stochastic simulation only occurred between the first nine cross sections ("s1" to "s9"). Guo et al. (2018), Shrestha et al. (2016), Schleiss et al. (2016), Estigoni (2016), Adam et al. (2015), Oh et al. (2015) also obtained good results when using a stochastic model to simulate sediment transport.

Also according to Figure 9, for 1000 different combinations of the "Q", "Q_{MM}" and "Q_{ST}" series, for the period comprehended between 2013 and 2017, the probability of siltation occurring between sections "s10" and "S21" is practically null. This corroborates Teixeira et al. (2020), who observed, using the same reduced model as this article, that there was no silting in the sections of the reservoir entrance (sections "10" to "21"). It can also be seen in Figure 9 that the real siltation observed in the reduced model (green line in Figure 9) has always been between the upper and lower limits of the stochastic simulation, being restricted between the 1st and 3rd quartiles, for all nine sections where siltation occurred. In almost all sections, except for section "2" (s2), the sediment height presented in the reduced model for 2017 was between the median siltation and that of the 3rd probability quartile. This indicates that the real siltation was between 50 and 75% of the highest values simulated stochastically.

With the stochastic simulation it is possible to estimate the probability of a certain silting height in a cross section occur, taking into account the uncertainties and the variability of the factors that interfere in this phenomenon. Thus, it can improve decision-making in reservoirs projects and promote their operation within safety margins, so that when the chances of certain levels of siltation occurring are known, the operation of the reservoir will not be compromised and/or even unviable.

For example, the stochastic simulation result of siltation in reservoirs can assist in a better dimensioning of its dead volume and also in choosing the level of its water intake. Supposing that the water intake of the SHP reservoir was positioned in the same vertical plane as cross section "1" (s1) and its sill was at the 0.10 m elevation (median value in that section, reduced model scale), in 50% of the simulations, that is, in 500 different combinations of flows and total solid discharges, the siltation would reach a higher level than 0.10 m, so that the water intake would be silted in this scenario. Obviously, for the same elevation assumed, in the other 500 simulations, the water intake would not be affected by the sediment. With that, it is up for the designers to decide the elevation of the hydraulic structures, but the stochastic simulation can help them, since it presents the risks of the structure being silted, which are associated with their decision. It should be noted that the SHP used in this article had its operations paralyzed exactly due to the siltation of its water intake. This structure was positioned between sections "2" and "3", sections which could have greater silted height, as shown by the stochastic model. That said, if the SHP project had used a stochastic method to simulate silting in its reservoir, the designer could have decided to position the water intake in another location, thus increasing the reservoir lifespan.

According to Figure 9, in sections "2" and "3" there were the largest dispersions of silting results. During the 1000 simulations, different flows and total solid discharges were used in each simulation. However, they were the same values for all sections, that is, for example, the flow in section "1" was obviously the same as in section "21". The sediment granulometry was also the same for all cross sections. The only two different physical parameters between the sections were the Manning roughness coefficient and the section geometry. However, the variation of the roughness coefficient cannot explain the high dispersion of the results in these two sections, since the calibrated Manning values are different, but very close. For example, the dispersion of results in section “3” is much greater than in “4”, but the Manning coefficients are very close: while section “3” has the value of 0.0352, section “4” has the value of 0.0357. Thus, the main reason for the high standard deviations in sections “2” and “3” is the geometry of these sections.

To confirm the previous statement, the hydraulic radiuses of the 21 cross sections are considered, and this parameter is affected by the geometry of the section and its water level. However, it was not possible to observe this parameter for the 1000 stochastic simulations, since the HEC-RAS controller did not allow this, as described in Dysarz (2018) and Leon & Goodell (2016). Thus, in HEC-RAS, the hydraulic radii of the 21 cross sections were obtained, for a silting simulation carried out with the daily flows of the historical series of the SHP, the simulated period being between 2013 and 2017. Since the simulation was done with daily flows for five years, 1825 flows were used, and consequently the same number of hydraulic radii was obtained, which are shown in Figure 10.

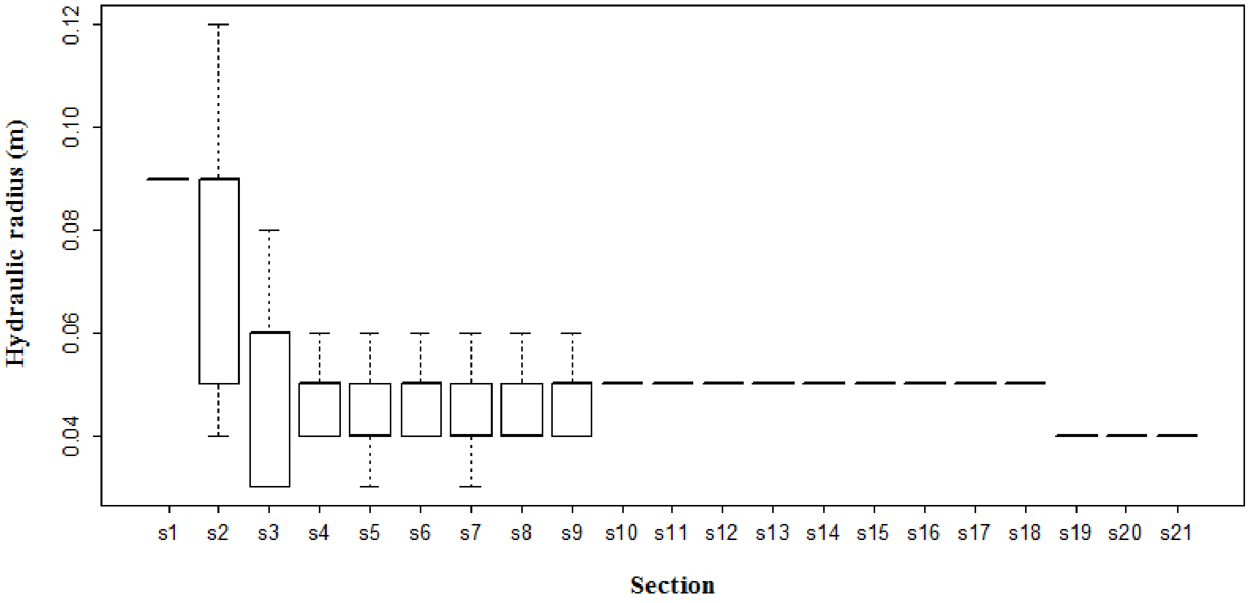

Figure 10. Hydraulic radii of the 21 cross sections, obtained from the daily flows between 2013 and 2017 (values converted to the reduced model).

It can be seen in Figure 10 that the dispersion of the hydraulic radii is similar to the siltation obtained through the stochastic simulation. Sections “2” and “3” presented the largest dispersions of hydraulic radii (Figure 10) and silting (Figure 9). Thus, it is observed that small variations in flow values, and consequently in water levels, caused large variations in the hydraulic radii of sections “2” and “3”, due to their geometries. Once the hydraulic radius varies, the shear stress and the capacity of sediment transport will also vary. In addition, it was observed in the reduced model that between these sections there was a vortex and resuspension of sediments, which contributed to the variation of the hydraulic radius. Alhasan et al. (2016) and Moran et al. (2013) also observed resuspension of sediments in a reduced model.

The simulations for the period comprehended between 2008 and 2012 were carried out in order to validate the developed stochastic method, and the dispersion of the results is shown in Figure 11. In the figure, the silted height shown was measured in relation to the lowest point of each cross section in the reduced model. The red line represents the siltation simulated in HEC-RAS, using the daily flow values and the sediment rating curve of the historical series of the SHP, for the period 2008-2012. Figure 11 also shows the median for each section, which is represented by the central line in each rectangle. The lower and upper limits of the rectangles represent, respectively, the 1st and the 3rd probability quartiles.

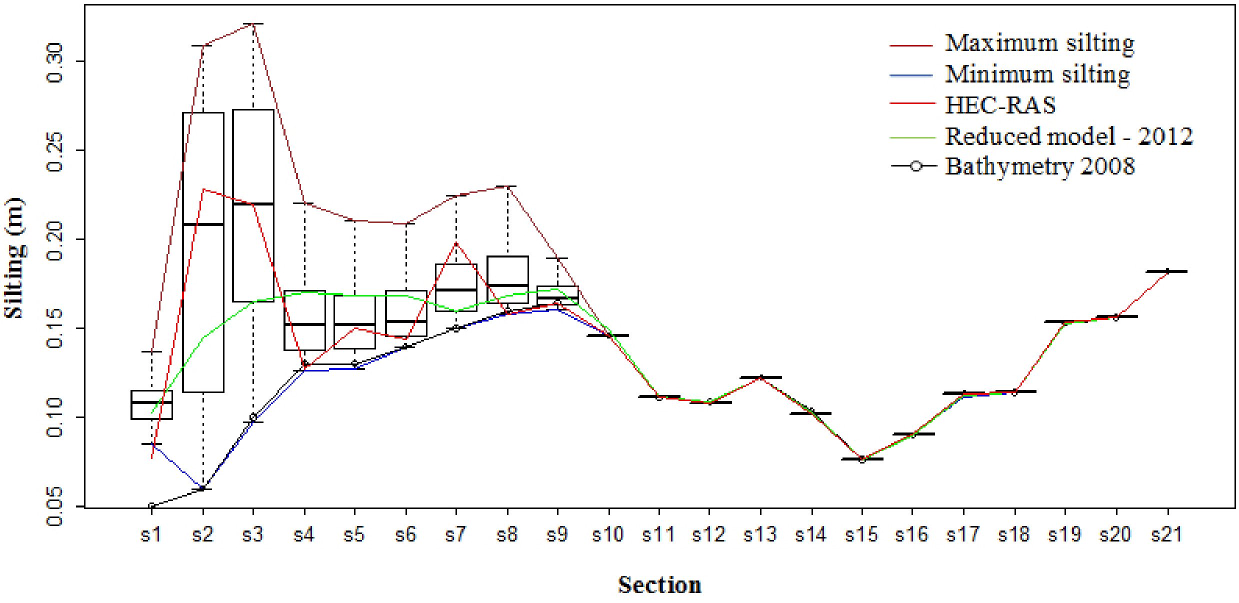

Figure 11. Result of the stochastic simulation, simulated in HEC-RAS and in the reduced model, for the siltation occurred between 2008 and 2013, in the 21 cross sections.

It can be seen in Figure 11 that the stochastic simulation indicated the tendency for the siltation not to occur between sections “10” and “21” (s10 to s21), which was also observed in the reduced model. Between sections “1” and “9” (s1 to s9), the silting obtained in the physical model was always between the maximum and minimum extremes of the 1000 simulations. This indicates that the stochastic simulation, by allowing the simulation of 1000 different combinations of hydrosedimentological data, covered the scenario that occurred. Thus, the stochastic simulation covered the combination of flows and total solid discharges used in the reduced model and it can also be observed that the developed stochastic method was valid for another period, in addition to the previous one used for its calibration (2013-2017).

When data from the historical series in the 2008-2012 period were used to deterministically simulate siltation in HEC-RAS, the result obtained (light red line in Figure 11), compared to what occurred in the physical model (green line), indicated that there was no silting between sections “10” and “21”, as it actually occurred. However, siltation was underestimated in sections “1”, “5”, “6” and “9” and overestimated in “2”, “3” and “7”. In sections “4” and “8”, the deterministic result of HEC-RAS showed that there was erosion, which in reality did not occur. Thus, it is clear that the siltation which was simulated in HEC-RAS was not what occurred in the reduced model in any of the sections where there was silted sediments (sections “1” to “9”).

With that, it is clear the contribution that the stochastic simulation can offer to reservoir projects, since today’s decisions are made based on deterministic models such as HEC-RAS, which, by providing only one result can underestimate or overestimate siltation, or even erode the reservoir bed. In a scenario of 1000 stochastic simulations, the siltation that occurred will be covered. In addition, from Figure 11, it can be seen that the real siltation has always been between the 1st and 3rd probability quartiles, a fact that represents another aid to the reservoir designer. That is, it is not possible to exactly predict silting since it is a complex phenomenon, variable in time and space, with parameters that present uncertainties in their values and require estimates for future scenarios. However, its probabilities of occurrence can be found in the cross sections of interest, with the variability of the results in the 1000 simulations indicating the places of greatest problem in predicting siltation, which induces the designer to be more conservative when positioning of some structures.

In this paper, thousands of synthetic series of ”Q” and ”Q_{ST}” were generated for the period 1967 to 2017. In HEC-RAS, all series were entered and thousands of silting results were generated for the period. However, only the results that occurred between 2008-2012 and 2013-2017 were extracted from the software, as these are the intervals in which the bathymetry was known. Other periods could be extracted from the results. Thus, the model allows simulating the designer’s period of interest. From this, temporal patterns in silting can be observed. In addition, only the silting profile was extracted from the HEC-RAS.

As thousands of simulations were performed on HEC-RAS, the results were automatically extracted. For this, the HEC-RAS controller used only allowed the extraction of the silted profile. However, the HEC-RAS presents other results. For example, it is possible to obtain, simultaneously, the variation of flow and silting over time. Thus, through the stochastic model developed in this research it is possible to model realistic sediment hysteresis patterns. In other words, it is possible to observe that the sediment temporal evolution is not necessarily directly proportional to the flow rate simultaneously observed. However, for this observation to be carried out, the HEC-RAS controller must be adapted so that other results, in addition to the silted profile, can be extracted from the software.

The method developed did not assess the impact of climate change on silting. However, the software used in the simulations (HEC-RAS) allows varying the water temperature and observing how this variation impacts the silting. Thus, this can be carried out in future research.

In addition, another research possibility is the combination of the stochastic model and a support vector machine models (SVM). SVM has been used to predict sediment concentration (Çimen 2008), sediment transport (Ebtehaj & Bonakdari 2016, Shafaghat & Dezvareh 2021) and sediment rate (Shafaghat & Dezvareh 2020). However, predictions were spot-on. That is, the authors cited did not use the SVM to estimate silting in longitudinal profiles and cross-sections. Thus, a research possibility is to use the SVM as a tool to estimate silting. In this case, the model’s input variables would be stochastically generated. In this way, it would be possible to obtain thousands of results and the probability of silting to occur.

CONCLUSION

Throughout this work, the fundamentals that guided the development of this research were presented, which aimed to present a stochastic method for estimating siltation in reservoirs. Based on the obtained results, the following can be stated:

- The stochastic model AR(1) for generating annual flows (Q) for the SHP adjusted well to the data, which proved to be stationary and follow a normal distribution. Total solid discharges were obtained from the flows generated by the AR(1) model. Thus, there was the generation of thousands of synthetic series containing the data of the two hydrosedimentological parameters which were considered stochastic;
- 1000 stochastic simulations of siltation were carried out, and this quantity was necessary, since fewer simulations did not promote the convergence of results in all cross sections. In addition, the geometry influenced the siltation results of the stochastic simulation, since in sections “2” and “3” in which the hydraulic radii suffered great variations, there was also greater dispersion of the silted heights.
- From the stochastic simulation, for the cross sections of interest, it was possible to obtain: dispersion, median, maximum, minimum and silting probability quartiles. Thus, it was observed that the simulated siltation in the physical model in the two evaluated periods (2008-2012 and 2013-2017) were always between the 1st and 3rd probability quartiles of the results that were generated stochastically. That is, the real siltation has always been greater than 25% of the results generated via stochastic simulation and smaller than 75% of them. Hence it can be noted that the stochastic result covered the scenario (flows and total solid discharges) that actually occurred.

Therefore, even if it is not possible to determine the exact siltation that occurs in a certain period in any cross section, the stochastic simulation indicates the probability of certain silting height occurring. In addition, stochastic simulation allows the uncertainties and variability of factors that interfere with silted sediment to be taken into consideration. The variability of the results in the simulations indicates the points of greatest problem in predicting siltation, inducing the reservoir designer to be more conservative in the positioning of some structures. With this, it will be possible to design and operate a reservoir within safety margins, knowing the chances of certain levels of siltation occurring. In addition, it will be possible to know the sections that are most likely to be silted, so that preventive and corrective measures, such as dredging, can be better planned and executed.

In this research, the results of silting occurred in a reduced model were used to validate the proposed stochastic model. The great advantage of physical modeling is the possibility of reproducing, in the laboratory, complex flows that occur in prototypes. However, the main limitation regarding the use of these models is the effects of the scales used to achieve the hydraulic similarity between the prototype and the model. In the reduced model used in this research, it was not possible to obtain similarity between the Froude and Reynolds number scales. In this case, the Reynolds number scale was not obeyed. Thus, it is recommended that those who are going to reproduce this article in other areas of study, that the relaxation in the scales be thoroughly studied, so that the model represents the reality of the prototype.

In future research, it is also recommended to use support vector machine models (SVM) for the stochastic simulation of silting.

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REFERENCES

ACKERS P & WHITE WR. 1973. Sediment transport: new approach and analysis. Journal of the Hydraulics Division 99(11): 2041-2060.

ADAM N, ERPICUM S, ARCHAMBEAU P, PIROTTON M & DEWALS B. 2015. Stochastic modelling of reservoir sedimentation in a semi-arid watershed. Water Resour Manag 29(3): 785-800.

ALHASAN Z, JANDORA J & RIHA J. 2016. Comparison of specific sediment transport rates obtained from empirical formulae and dam breaching experiments. Environ Fluid Mech 16(5): 997-1019.

BONAKDARI H & EBTEHAJ I. 2016. A comparative study of extreme learning machines and support vector machines in prediction of sediment transport in open channels. Int J Eng 29(11): 1499-1506.

BOX GE, JENKINS GM, REINSEL GC & LJUNG GM. 2015. Time series analysis: forecasting and control. J Wiley & Sons.

BRAGA BB, DE CARVALHO TRA, BROSINSKY A, FOERSTER S & MEDEIROS PHA. 2019. From waste to resource: Cost-benefit analysis of reservoir sediment reuse for soil fertilization in a semiarid catchment. Sci Total Environ 670: 158-169.

CÂMARA RKC, ROCHA EJP, PROTÁZIO JMB, QUEIROZ JC, RIBEIRO WMDN, SIQUEIRA IS & LIMA AMMD. 2016. Hydrological stochastic modeling applied to the Tocantins River to the city of Marabá (PA). Rev Bras Meteorol 31: 11-23.

CARVALHO LS, SALIBA APM, SANTOS RSF, HASELBAUER M, VELASCO D, VIANA EMF, MARTINEZ CB, COSTA MEF & FREITAS FL. 2014. Desenvolvimento do projeto do modelo reduzido da PCH Salto do Paraopeba. Congresso Latinoamericano de Hidráulica.

CARVALHO NDO, GUILHON LG & TRINDADE PA. 2000. O assoreamento de um pequeno reservatório-Itiquira, um estudo de caso. Revista Brasileira de Recursos Hídricos-RBRH 5: 69-79.

CHATFIELD C. 2000. Time-series forecasting. Chapman and Hall/CRC.

ÇIMEN M. 2008. Estimation of daily suspended sediments using support vector machines. Hydrol Sci J 53(3): 656-666.

DYSARZ T. 2018. Application of Python Scripting Techniques for Control and Automation of HEC-RAS Simulations. Water 10(10): 1382.

ENGELUND F & HANSEN E. 1967. A monograph on sediment transport in alluvial streams. Technical University of Denmark 0stervoldgade 10, Copenhagen K.

ESTIGONI MV. 2016. Uso de modelagem de transporte de sedimentos e técnicas de hidrologia estatística para redução de incertezas nos estudos de assoreamento de reservatórios: estudo de caso do reservatório da PCH Mogi-Guaçu-SP. Ph.D. thesis. Universidade de São Paulo.

GIBSON S, SÁNCHEZ A, PIPER S & BRUNNER G. 2017. New one-dimensional sediment features in HEC-RAS 5.0 and 5.1. In: World Environmental and Water Resources Congress 2017, p. 192-206.

GUO A, CHANG J, WANG Y, HUANG Q & ZHOU S. 2018. Flood risk analysis for flood control and sediment transportation in sandy regions: A case study in the Loess Plateau, China. J Hydrol 560: 39-55.

HABETS F, MOLÉNAT J, CARLUER N, DOUEZ O & LEENHARDT D. 2018. The cumulative impacts of small reservoirs on hydrology: A review. Sci Total Environ 643: 850-867.

HAGER WH. 2018. Bed-load transport: advances up to 1945 and outlook into the future. J Hydraul Res 56(5): 596-607.

JULIEN PY. 2002. River mechanics. Cambridge University Press.

KURIA F & VOGEL R. 2015. Uncertainty analysis for water supply reservoir yields. J Hydrol 529: 257-264.

LAURSEN EM. 1958. The total sediment load of streams. The University of Iowa.

LEON AS & GOODELL C. 2016. Controlling hec-ras using matlab. Environ Model Softw 84: 339-348.

MAAVARA T, PARSONS CT, RIDENOUR C, STOJANOVIC S, DÜRR HH, POWLEY HR & VAN CAPPELLEN P. 2015. Global phosphorus retention by river damming. Proc Natl Acad Sci 112(51): 15603-15608.

MAMEDE GL, GUENTNER A, MEDEIROS PH, DE ARAÚJO JC & BRONSTERT A. 2018. Modeling the effect of multiple reservoirs on water and sediment dynamics in a semiarid catchment in Brazil. J Hydrol Eng 23(12): 05018020.

MEYER-PETER E & MÜLLER R. 1948. Formulas for bed-load transport. In: IAHSR 2nd meeting, Stockholm, appendix 2. IAHR.

MIRANDA RD. 2011. A influência do assoreamento na geração de energia hidrelétrica: estudo de caso na usina hidrelétrica de Três Irmãos-SP. São Carlos-SP.

MORAN AD, ABDERREZZAK KEK, MOSSELMAN E, HABERSACK H, LEBERT F, AELBRECHT D & LAPERROUSAZ E. 2013. Physical model experiments for sediment supply to the old Rhine through induced bank erosion. Int J Sediment Res 28(4): 431-447.

NAGHETTINI M & PINTO ÉJDA. 2007. Hidrologia estatística. CPRM.

OH J, TSAI CW & CHOI SU. 2015. Quantifying the uncertainty associated with estimating sediment concentrations in open channel flows using the stochastic particle tracking method. J Hydraul Eng 141(12): 04015031.

RIBEIRO JC & SALOMÃO FXT. 2001. A Morfopedologia aplicada ao diagnóstico e prevenção dos processos erosivos lineares da bacia hidrográfica do Alto Rio da Casca. In: Anais do VII Simpósio Nacional de Controle de Erosão. Goiânia.

SCHLEISS AJ, FRANCA MJ, JUEZ C & DE CESARE G. 2016. Reservoir sedimentation. J Hydraul Res 54(6): 595-614.

SHAFAGHAT M & DEZVAREH R. 2020. Predicting the sediment rate of Nakhilo Port using artificial intelligence. Int J Coast Offshore Eng 4(2): 41-49.

SHAFAGHAT M & DEZVAREH R. 2021. Support vector machine for classification and regression of coastal sediment transport. Arab J Geosci 14(19): 1-20.

SHRESTHA B, COCHRANE TA, CARUSO BS, ARIAS ME & PIMAN T. 2016. Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. J Hydrol 540: 1088-1104.

TEIXEIRA EKDC, RINCO AV, COELHO MMLP, SALIBA APM, PINTO EJDA & FURTADO LM. 2020. Methodology for physical modeling of reservoir sedimentation. RBRH 25.

THAKKAR H & BHATTACHARYYA S. 2006. Reservoir siltation in India: Latest studies. Dams, Rivers and People 4(7-8): 1-15.

TOFFALETI F. 1966. A procedure for computation of total river sand discharge and detailed distribution, bed to surface. Committee on Channel Stabilization. US Army Corps of Engineers.

USACE. US ARMY CORPS OF ENGINEERS. 2016. HEC-RAS, river analysis system hydraulic reference manual. Hydrologic Engineering Center (HEC), Version 50, p. 960.

WILCOCK PR & CROWE JC. 2003. Surface-based transport model for mixed-size sediment. J Hydraul Eng 129(2): 120-128.

YANG CT. 1973. Incipient motion and sediment transport. Journal of the hydraulics Division 99(10): 1679-1704.

YANG CT. 1984. Unit stream power equation for gravel. J Hydraul Eng 110(12): 1783-1797.

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