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Software for reservoir silting forecast based on sediment trapping efficiency methods

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Abstract

Silting is one of the main problems of reservoirs formed by dams. These water bodies have stagnant velocity fields, resulting in high capacity for growth of bottom deposits. The focus of this work is the silting forecast of Bom Jardim reservoir, located in Uberlândia, Minas Gerais state, Brazil. Estimates were based on classical methods of sediment trapping efficiency. Sediment input is introduced by curves that relate solid loads with inlet flows. The affluent flow rates are based on synthetic series obtained by stream flow regionalization. In the context of this paper, the calculations were systematized in the SILTINGZ software, a computer simulator able of estimating the spatial and temporal advance of sediment deposits in reservoirs. In this model, the algorithms are coded in the Visual Basic for Applications (VBA) language. The software is able to use four classical methods in order to calculate the sediment trapping efficiency. The results revealed monthly silting rates between 916 m^3/month and 1040 m^3/month, including the latent possibility of forming localized sandbanks. For periods over 50 years, the simulation predicts evolution of considerable deposits between the half of the reservoir and the dam. The main sandbanks are formed immediately downstream of the confluence of Bom Jardim stream. The useful volume of the reservoir may be gradually affected after a period of 56 to 64 years. This predictive study considered stationary conditions of contributing basins to the reservoir. Actual silting rates can be amplified with deforestation or delayed by reforestation in these watersheds.

Keywords: Hydrology, fluvial hydraulics, sediment transport, sediment trapping, computational simulation.

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INTRODUCTION

Rivers and streams are long water bodies, with a sloping bottom, in which the widths are many orders of magnitude smaller than the length. The geometric differences are decisive for hugely different flow patterns between rivers and reservoirs. In stream flows, the currents keep suspended solids and cause shear stresses over the bed, dragging bottom sediments. In sections where the shearing stresses are higher, such as in high slope stretches, erosion and resuspension processes can occur. On the other hand, in reservoirs, the relative stagnation of water contributes to the sediment deposition. In addition, resuspension processes are inhibited by the low magnitude of shear stresses and by thermal stratification, mainly in spring and summer. The consequence is the formation of bed deposits, which volumes increases gradually with time. The sediments are carried into reservoirs from the tributaries or directly through runoff. The silting of these water bodies is an inexorable process, but it can be amplified by human actions over watersheds. Such actions change land uses, usually removing native vegetation for urbanization, agriculture and livestock. This increases erosive processes in watersheds, increasing the sediment loads discharged into the reservoirs.

Silting is a major concern for reservoir managers for hydroelectric generation and for those linked to water supply or irrigation. In fact, the growth of bottom deposits can block the water intake structures and can reduce the useful volume of the lake. For this reason, it is important to predict the accumulation of bottom sediments and their spatial and temporal evolution. This allows the identification of areas most susceptible to the formation of sand banks, guiding actions to mitigate these problems. Studies such as Martins (2018) show that, although dredging is a temporary solution, partial silting control can be applied in a diffuse way, in the watershed itself, with appropriate management and reforestation practices.

According to Carvalho *et al.* (2000), the most appropriate methods for quantifying silting depend on the objectives to be met. In the operation phase, with reservoirs already formed, there is great interest in locating preferential deposition zones, checking whether they are close to the water intake structures. In this case, periodic topobatimetric surveys are important to verify changes in reservoir bottom. In general, these authors recommend that the desirable frequency of surveys should be 2 years for small reservoirs, with volumes less than 10 hm^3. For reservoirs with volumes greater than 100 hm^3, this frequency can be extended to 10-year intervals. Randle *et al.* (2017) comment that another field technique consists of systematically monitoring the discharges of affluent and effluent sediments, in addition to periodic bathymetry. However, topobatimetric surveys require financial resources, equipment and specialized technical staff, factors that make frequent monitoring difficult. In addition, quantifications of total sediment loads are performed with instantaneous sampling of flow and suspended sediment concentrations, added to techniques to estimate bed transport. Such instantaneous surveys may not capture flood events, in which the largest inflows of sediments occur into the reservoirs. The point is that there are no hydrosedimentometric stations in all tributaries of the reservoirs. In addition, the historical record of data, mainly of sediment discharges, is still scarce, with short series.

In the design phase of reservoirs, the main objective is to predict silting rates and the useful life of the project. According to Randle *et al.* (2017), should be quantified the volume of sediments deposited over a period, that is typically in the range of 50 to 100 years. This interval may be exceeded for some reservoirs. In this case, modeling and simulation of silting are essential procedures.

In this paper are presented prediction methods based on the classic empirical theory of sediment trapping efficiency. Additionally, techniques for regionalization of average monthly flow are treated. The estimation of the synthetic series of reservoir inflows is based on the correlation between fluviometric data and monthly rainfall data. The main characteristics of the computational model SILTINGZ are addressed. This program synthesizes algorithms for prediction of reservoir silting. This tool was coded in Visual Basic for Applications (VBA) and applied to spreadsheets.

THE BOM JARDIM RESERVOIR AND THE TARGET WATERSHEDS

The watershed of the Bom Jardim stream, is in Triângulo Mineiro region, between the coordinates 18 ° 36 ’and 19 ° 22’ (south latitude) and 47 ° 57 ’and 48 ° 33’ (west longitude) (Figure 1). The Bom Jardim reservoir, located at south of the city of Uberlândia, was selected as the target of the proposed studies. The justification lies in the fact that this water body constitutes one of the city's water sources, whose municipality is the second most populous in the Minas Gerais state. Approximately 40% of the water destined for the city's public supply is collected from this reservoir. The dam that forms the reservoir is located 1,5 km upstream of the confluence of the Bom Jardim stream with the Uberabinha river.

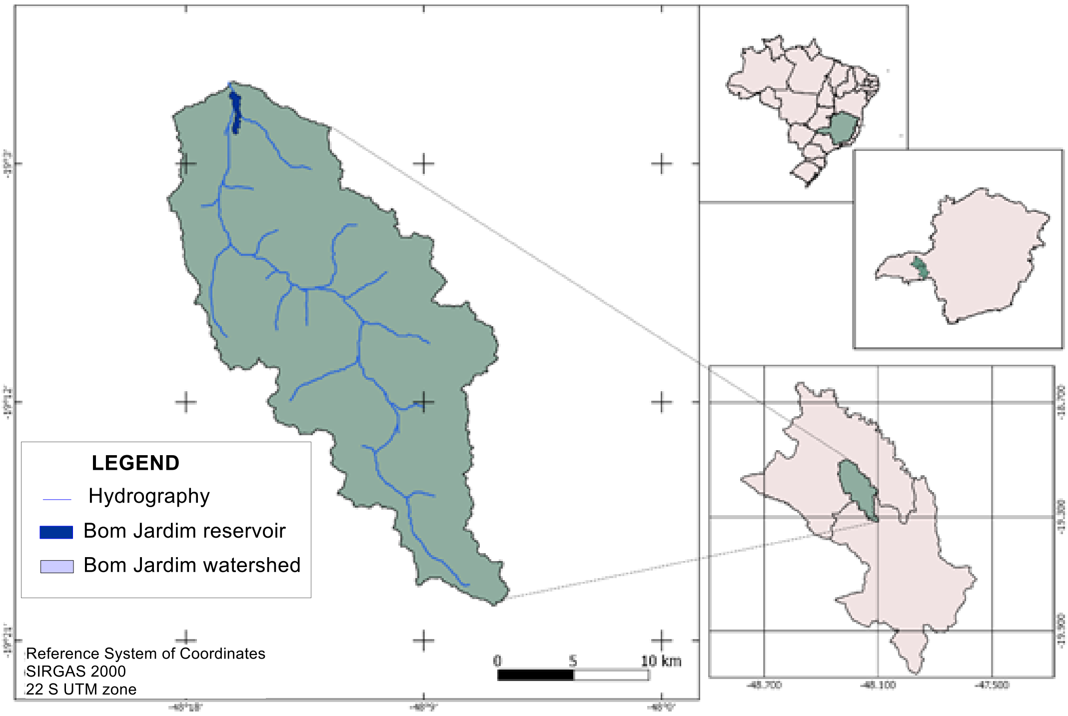


Figure 1 – The Bom Jardim watershed

Bathymetric survey, carried out from planialtimetric map existing before the reservoir, allowed to map the bottom of the reservoir (Figure 2), supporting the calculation of storage capacity. The main water inlets into the reservoir occur from five points: RBJ (main inlet section in the Bom Jardim stream delta, which drains an area of 333.25 km^2); ENX (Enxada stream delta, with drainage area of 31 km^2); E1 (small stream from the left bank, with a contributing area of 2 km^2); E2 (another small stream on the left bank, with drainage area of 8.98 km^2) and D1 (small stream on the right bank, whose contributing area is 2.6 km^2). These contributing areas, called target watersheds, generate sediment loads that are injected into the reservoir. The outlet sections in target basins do not have systematic flow records. In this context, the flow forecast at these points was based on historical records extracted from fluviometric stations located in neighboring basins, here called source watersheds. Therefore, flow regionalization is necessary. This procedure is described in the following section of this paper.

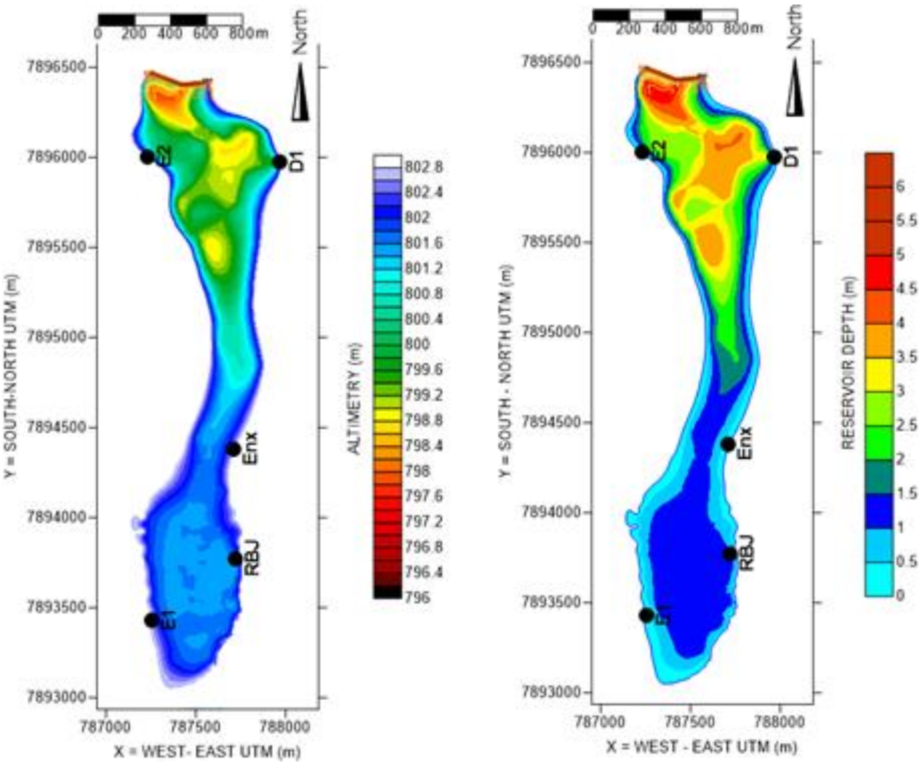


Figure 2 – Bathymetry of Bom Jardim reservoir

REGIONALIZATION OF MONTHLY AVERAGE FLOWS

There are no historical records of affluent flows into the Bom Jardim reservoir. The field data available in previous works such as those by Martins (2018) and Santos (2018) are instantaneous and still insufficient to generate synthetic flow series. Thus, to estimate the inflows into the reservoir, the analysis of regionalization was carried out, using historical fluviometric records in neighboring rivers and streams. The viability of this study is due to fluviometric and pluviometric data provided by the Agência Nacional de Águas (ANA), in the Hidroweb online system, in addition to series of flows from the upper Bagagem river, not registered in the referred system.

Selection of source watersheds

Nine fluviometric stations were chosed in source basins, close to the Bom Jardim reservoir. From the daily flow records, the average flows of each month (average monthly flows) were computed. The source stations are shown in Table 1 and mapped in Figure 3.

The watershed areas are geometric factors that directly influence the flow of water bodies. Therefore, the larger the drainage area, the greater the flow in a given cross section of a river. Thus, to establish the influence of the basin area on the river flow regime, the specific monthly discharges, for each fluviometric station, were taken as variables to be regionalized:

$$Q^{*}_{k} = Q_{k} / A \qquad (1)$$

At the Equation (1), Q^{*}_{k} is the specific discharge for the k month, Q_k is the average monthly flow for that month and A is the area of the contributing basin to the source fluviometric station. The specific discharge is quantified in $m^3/s/km^2$.

Table 1 – Source fluviometric stations

Fluviometric station (source)	**River**	**Data period (date)**	**Contributing area A (km^2)**
1 - Pontilhão	Bagagem	01/2005 to 12/2011	17.52
2 - Iraí de Minas	Bagagem	01/2005 to 12/2011	91
3 - Ponte Velha	Bagagem	01/2005 to 12/2011	262.42
4 - Israel	Bagagem	01/2005 to 12/2011	289.95
5 - Uberaba	Uberaba	10/1976 to 02/2016	566
6 - Sucupira	Uberabinha	01/1953 to 12/1965	716
7 - Ponte Preta	Jordão	10/1952 to 6/1960	762
8 - Ponte da Antinha	Capivara	01/1953 to 08/1992	1270
9 - Fazenda Paraíso	Tijuco	01/1953 to 02/2016	1510

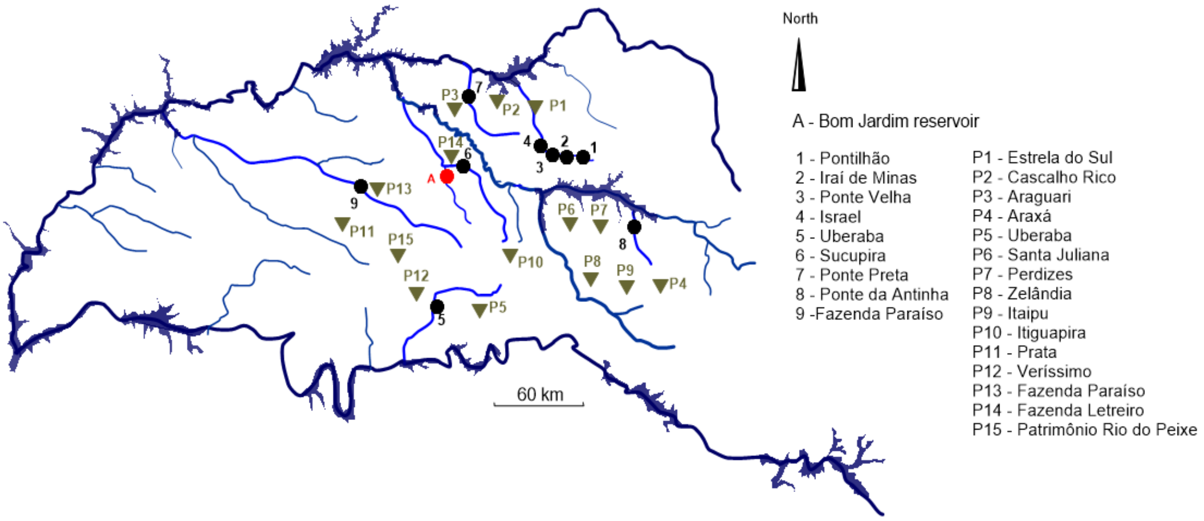


Figure 3 – Fluviometric and pluviometric source stations near the Bom Jardim reservoir

Pluviometric stations

The purpose of the regionalization rule is to relate the specific monthly flow with the monthly precipitation transported to the centroid of the watershed. Thus, knowing rainfall data near a basin, it will be possible to estimate the flow in the draining watercourse. In this sense, using the Hidroweb system, rainfall stations close to each source basin were chosen. For these, the total rainfall in each month was computed. Subsequently, the historical series of monthly precipitation were interpolated, allowing to obtain rain series for the centroid of each source watershed. The stations used for this purpose and their codes in the Hidroweb system were: Estrela do Sul (1847001), Cascalho Rico (1847007), Araguari (1848010), Araxá (1946015), Uberaba (1946015 e 1947016), Santa Juliana (1947001), Perdizes (1947007), Zelândia

(1947009), Itaipu (1947025), Itiguapira (1947026), Prata (1948018), Veríssimo (1948003), Fazenda Paraíso (1948005), Fazenda Letreiro (1948006) and Patrimônio Rio do Peixe (1948016).

Specific discharges *versus* precipitation at source watersheds

For each source watershed, the specific discharge records (Q^*_k) were compared, using dispersion graphs, with monthly precipitation values in its centroid (P_k). For this, it was necessary to list only the data in corresponding months. For each source station, the dispersion diagrams suggest moreless evident trends between specific discharge and monthly precipitation. In all tested cases, linear trend curves provided the highest determination coefficients (R^2). The trend lines established in the diagrams (Q^*_k x P_k) (Figure 4) were important in this regionalization analysis.

(a) Pontilhão station
(A = 17.52 km^2)

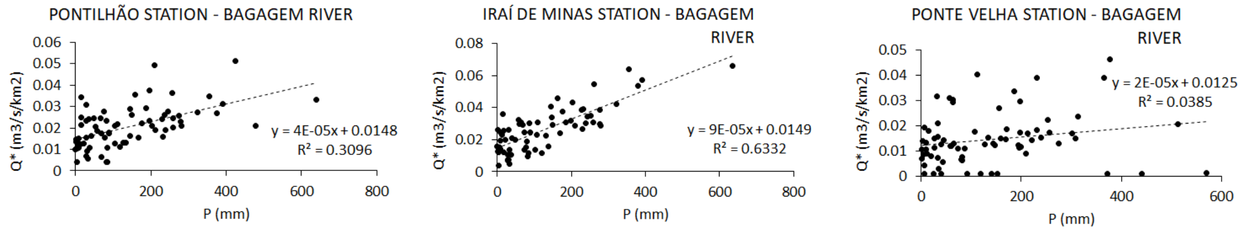
Correlation coefficient = 0.560

(b) Iraí de Minas station
(A = 91 km^2)

Correlation coefficient = 0.796

(c) Ponte Velha station
(A = 262.42 km^2)

Correlation coefficient = 0.196



(d) Israel station
(A = 289.95 km^2)

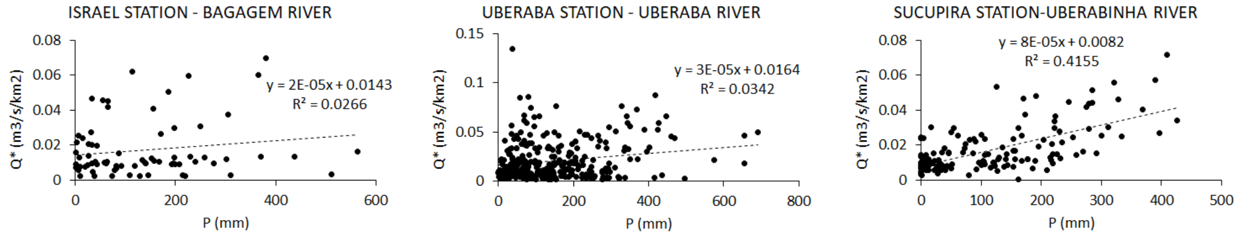
Correlation coefficient = 0.160

(e) Uberaba station
(A = 566 km^2)

Correlation coefficient = 0.185

(f) Sucupira station
(A = 716 km^2)

Correlation coefficient = 0.640



(g) Ponte Preta station
(A = 762 km^2)

Correlation coefficient = 0.440

(h) Ponte da Antinha station
(A = 1270 km^2)

Correlation coefficient = 0.608

(i) Fazenda Paraíso station
(A = 1510 km^2)

Correlation coefficient = 0.315

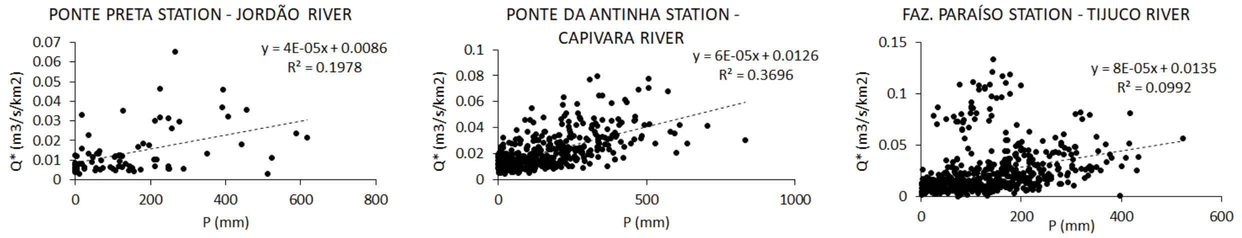


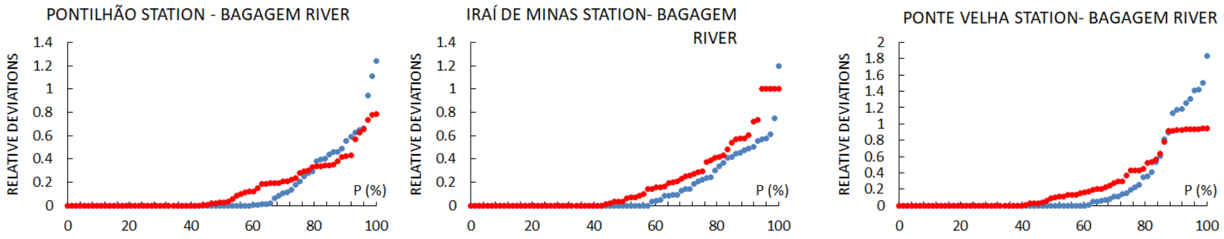
Figure 4 – Scatter diagrams Q^*_k x P_k and linear regression corresponding to the source stations

Then, relative deviations of recorded flows were calculated, in relation to the trend curve (QLT^*_k). These deviations are positive and negative according to:

$$\text{If } Q^*_k \geq QLT^*_k : D^+ = \left(Q^*_k - QLT^*_k\right) / QLT^*_k$$
$$\text{If } Q^*_k \leq QLT^*_k : D^- = \left(Q^*_k - QLT^*_k\right) / QLT^*_k \qquad (2)$$

In the set of Equations (2), Q^*_k represents the measured flow in the source station, for k month; QLT^*_k is the flow rate estimated by the linear trend line, D^+ and D^-, are positive and negative relative deviations from the trend line.

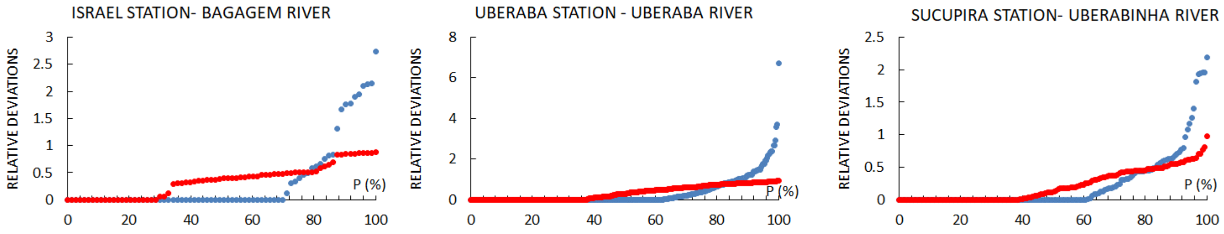
The relative deviations, calculated according to Equation (2), were arranged in ascending order, establishing a permanence interval from 0 to 100% for these values. Thus, the highest value (in module) for the deviation corresponds to 100% of permanence, while the lowest value corresponds to 0. This procedure, when applied to positive relative deviations (D^+) and to module of negative relative deviations (D^-) resulted in permanence diagrams, as shown in Figure 5. This permanence curves (D x $P\%$) describe the probability of occurring deviation values less than or equal to a certain value. For example, for the Pontilhão station (Figure 5a), there is 80% of probability to positive or negative deviations stay below 0.38 and 0.34, respectively. This indicates that the linear trend line between Q^*_k and P_k, at this source station, has a good ability to represent the measured data – the relationship between the specific flow and the monthly precipitation. In flow regionalization procedure, proposed in this paper, the permanence of 80% was used as reference.



(a) Pontilhão station
$D^+_{80} = 0.38$
$D^-_{80} = 0.34$ (absolut value)

(b) Iraí de Minas station
$D^+_{80} = 0.34$
$D^-_{80} = 0.42$ (absolut value)

(c) Ponte Velha station
$D^+_{80} = 0.35$
$D^-_{80} = 0.52$ (absolut value)



(d) Israel station
$D^+_{80} = 0.62$
$D^-_{80} = 0.52$ (absolut value)

(e) Uberaba station
$D^+_{80} = 0.64$
$D^-_{80} = 0.74$ (absolut value)

(f) Sucupira station
$D^+_{80} = 0.45$
$D^-_{80} = 0.45$ (absolut value)

(g) Ponte Preta station
$D^+_{80} = 0.44$
$D^-_{80} = 0.54$ (absolut value)

(h) Ponte da Antinha station
$D^+_{80} = 0.35$
$D^-_{80} = 0.39$ (absolut value)

(i) Fazenda Paraíso station
$D^+_{80} = 0.26$
$D^-_{80} = 0.61$ (absolut value)

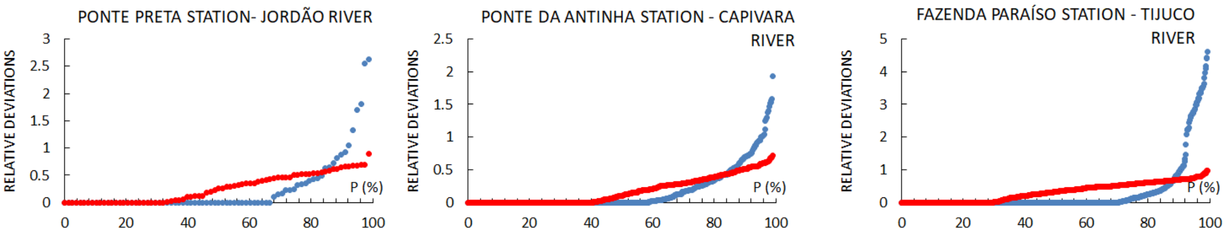


Figure 5 – Permanence curves for relative deviations: red points represent negative values and blue points represent positive values

The procedures described in this item were applied separately, for each source watershed.

Flow regionalization rule

The regionalized equation that expresses the variation of Q^*_k versus P_k has the regression line as a base function but introduces the maximum relative deviations (with 80% of permanence) as the maximum amplitude of fluctuations around this line. As nine fluviometric stations were analyzed, it was decided to use an average regression line. Thus, the regionalization function for the specific discharge can be written as:

$$Qr^*_k = QLT^*_{Mk}\cdot\left(1+\alpha\cdot D^+_{80\max}-\beta\cdot D^-_{80\max}\right) \qquad (3)$$

In Equation (3), Qr^*_k is the specific regionalized discharge for the k month, $QLT^*_{M\,k}$ is the specific discharge obtained by linear regression (average trend line of all source stations), α and β are random numbers that vary between 0 and 1. D^+_{80max} and D^-_{80max} are the largest relative deviations (positive and negative) obtained among all the analyzed source stations (0.64 and 0.74, respectively). The parameters α and β were inserted to introduce randomness in rain-flow relationship.

As shown at Figure 2, in the specific case of the Bom Jardim reservoir, the main water inflows occur at five points: RBJ, ENX, E1, E2 and D1. With regionalization studies, the function applied to generate the synthetic series of flows injected into the reservoir is described by:

$$Qr^*_k = (Q/A) = (\alpha\cdot P+b)\cdot\left(1+\alpha\cdot D^+_{80\max}-\beta\cdot D^-_{80\max}\right) \qquad (4)$$

In Equation (4), Qr^*_k (m^3/s/ km^2) is the specific discharge, the relationship between the flow (Q) and the watershed area (A); P *(mm)* is the monthly precipitation at centroid of the basin; a and b are regional adjustable parameters of the mean regression line. For the analyzed place (rivers of Triângulo Mineiro region) such coefficients are, respectively $4.9290\cdot 10^{-5}$ and 0.0128643.

SEDIMENT KEY CURVE

The sediment injection into the reservoir is modeled by a curve that establishes the relationship between solid loads and affluent flow – key sediment curve. However, inlet sections of the Bom Jardim reservoir do not have key sediment curves. In this sense, it was used the curve simulated by Martins (2018), based on application of the *Soil and Water Assessment Tool* (SWAT) software (Figure 6).

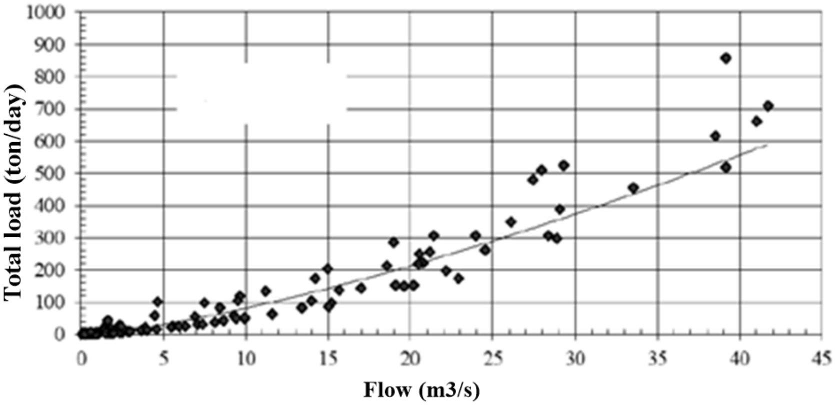


Figure 6 – Sediment key curve simulated for Bom Jardim reservoir (Martins, 2018)

The curve simulated by Martins (2018) was adapted, dividing the sediment load and the flow by the contribution area of reservoir. This procedure generated the key curve for specific sediment load as function of the specific discharge and can be interpolated by a polynomial function, as follows:

$$Qs^{*} = \left(Qs/A\right) = c \cdot \left(Q^{*}\right)^{2} + d \cdot Q^{*} \qquad (5)$$

In Equation (5), Qs^{*} (ton/day/km^2) is the specific sediment load, A is the area of the contribution basin (km^2), while $c = 104.4707$ and $d = 5.881465$ are regional parameters, derived from polynomial interpolation.

THE SILTINGZ SOFTWARE

The SILTINGZ program was built with workheets, with algorithms coded in the VBA language. This application consists of six worksheets, each with specific functions, ranging from the registration of input data to results presented graphically and numerically. In this context, worksheets are used only for data entry and attachment of results. All calculation procedures are performed by subroutines and functions written in VBA. Figure 7 illustrates some of the worksheets of the software.

In worksheet 0, the simulator startup screen is shown. The worksheet 1 summarizes the main geometric aspects that must be registered by the user, such as the water level, number of compartments for reservoir discretization, digital bathymetric model (DBM) and the contours of the reservoir. From this set of information, the program calculates the volume of the reservoir, including its distribution by compartments. Also, in this woksheet, must be inserted the input coordinates of the main tributaries and the areas of their contribution basins. This creates conditions for estimating the flows injected into the reservoir from the affluent channels. This procedure is done using the flow regionalization technique, described in the previous item and developed outside the program. In worksheet 2, monthly rainfall serie is recorded. This will support the calculation of flows and loads of injected sediments over the simulation period. These results are presented in worksheet 3. In worksheet 4, the silting simulation itself is done. In this worksheet, the results of flows and loads of affluent sediments, volumes and average heights of the deposits and the total silted volume for a given time are attached. In worksheet 5, numerical results and silting graphs, calculated by different methods, are attached.

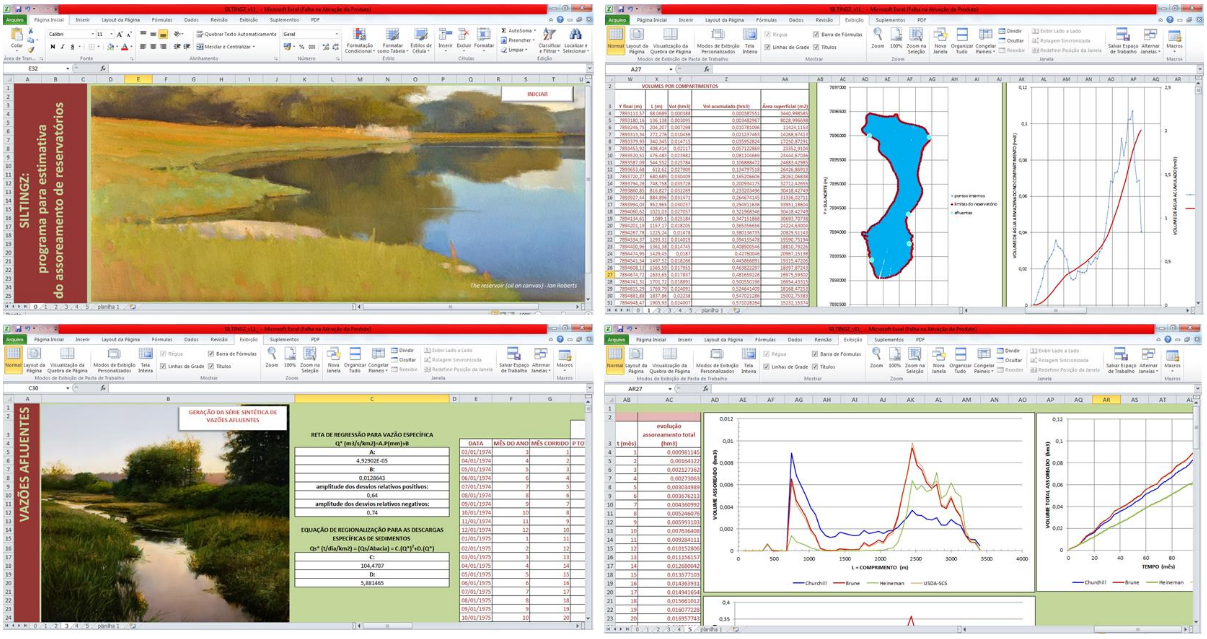


Figure 7 – Some worksheets of SILTINGZ software

SEDIMENT TRAPPING EFFICIENCY

Sediment trapping efficiency (E) is theoretically defined as the relative difference between the affluent and effluent solid loads from the reservoir, that is:

$$E = \left(Qs_{in} - Qs_{out} \right) / Qs_{in} \qquad (6)$$

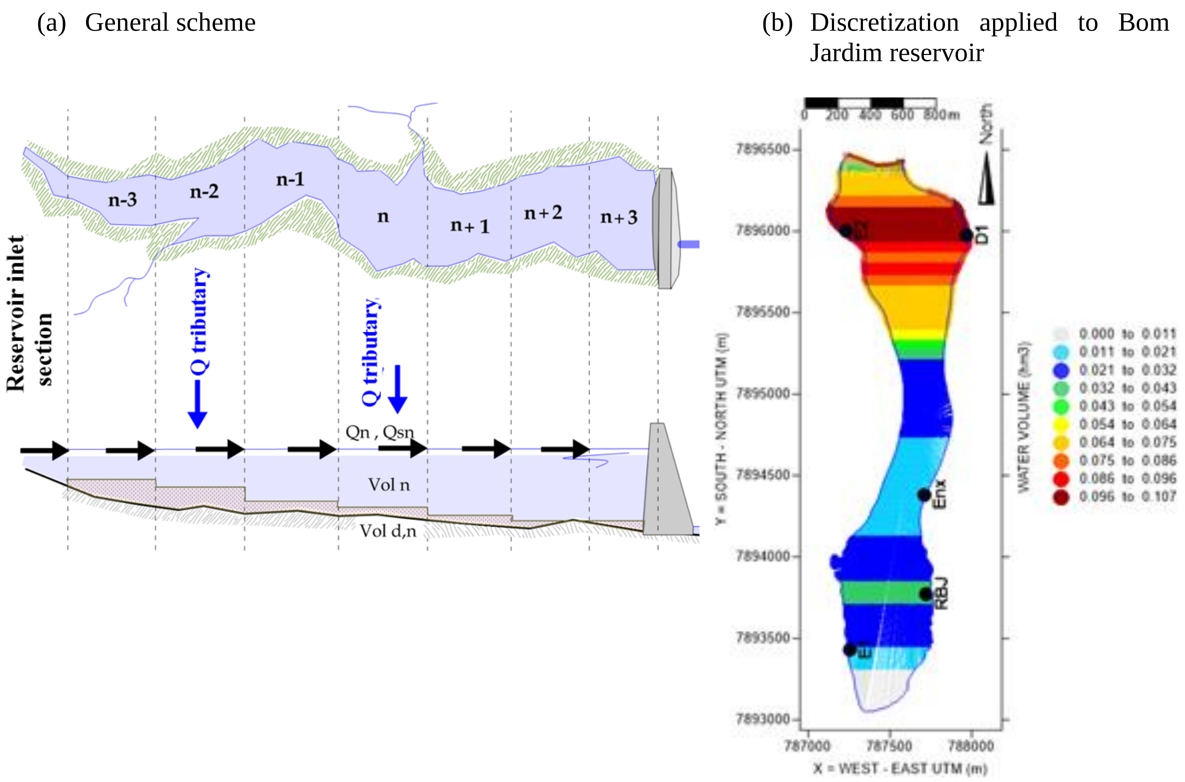
In Equation (6), Qs represents sediment mass loads entering (Qs_{in}) and leaving (Qs_{out}) the reservoir, measured in units of mass per unit of time.

Minear and Kondolf (2009) affirm that trapping efficiency depends on the characteristics of the affluent sediment, the inflows, and the geometric characteristics of the reservoir. The feed data for the SILTINGZ program is based on these three standards. Van Rijn (2013) points out that long reservoirs can be discretized in compartments, so that affluent flows and loads, retention efficiency and deposited volumes are quantified for each sector. Thus, it is possible to locate, with more details, the areas suitable for silting. This possibility of discretization, outlined in Figure 8, is an attribute of SILTINGZ software.

In the reservoir division scheme, Q_n and Qs_n are, respectively, flows and sediment loads affluent to n compartment. $Vol_{\ n}$ and $Vol_{\ d,\ n}$ are volume of water and silted volume of each sector. In this case, the Bom Jardim reservoir was divided at 25 compartments.

The simulation advances in time, with monthly increments. In this sense, the flows of each sector for a k month ($Q^k{}_n$) are fed by upstream compartment and by eventual lateral tributaries ($Q^k{}_{tributary}$) These represent average monthly flows, calculated by regionalization procedures previously exposed. With the reservoir discretization, the trapping efficiency ($E^k{}_n$) is calculated for each sector, so that the flows and effluent loads from one compartment (n) represent input variables for the next compartment ($n + 1$). Sediment loads transferred between two sectors are calculated as:

$$Qs^k{}_{n+1} = Qs^k{}_n \cdot \left(1 - E^k{}_n \right) \qquad (7)$$



(a) General scheme

(b) Discretization applied to Bom Jardim reservoir

Figure 8 – Reservoir discretization in compartments

These sediment loads are quantified in units of mass per unit of time (kg/s, kg/month, ton/day, ton/month). Once the solid loads have been quantified, the retained sediment mass (Ms^k_n) and the increase in silted volume in the compartment ($Vol^k_{d,n}$) are quantified by:

$$Ms^k{}_n = \left(Qs^k{}_n - Qs^k{}_{n+1}\right)\cdot \Delta t \tag{8}$$

$$\Delta Vol^k{}_{d,n} = Ms^k{}_n / \rho^k{}_n \tag{9}$$

In Equations (8) and (9), Δt is the monthly time interval for each time step, what should be registered with compatible units in relation to sediment load. The density of deposits ($\rho^k{}_n$) allows the transformation of mass trapped in deposited volume. This parameter depends on the fractions of clay, silt and sand present in the deposits. The deposit density changes with time due to compaction of the lower layers by the most recent deposits. In SILTINGZ, the density of deposits is calculated by the set of Equations (10), recommended for reservoirs with permanently submerged sediments (CARVALHO *et al.*, 2000):

$$K_a = 0.256\cdot(clay) + 0.091\cdot(silt)$$

$$\rho_0 = \left[0.416\cdot(clay) + 1.121\cdot(silt) + 1.554\cdot(sand)\right]\cdot 1000$$

$$\rho^k = \rho_0 + 0.4343\cdot K_a \cdot \left[t/(t-1)\cdot \ln(t) - 1\right] \tag{10}$$

In this set of equations, *clay*, *silt* and *sand* are granulometric fractions of these classes in deposits. K_a is an auxiliary parameter, ρ_0 is the deposit density at the beginning of the simulation ($t = 0$) and t is the simulation time, measured in months. In Equation (10), ρ^k is quantified in kg/m^3. Costa (2012) found that silted volumes, in general, are little sensitive to density variations. Finally, over a simulation period (T), the silted volume in each compartment can be calculated as:

$$Vol_{d,n}^{k} = \sum_{t=0}^{T} \Delta Vol_{d,n}^{k} \tag{11}$$

EMPIRICAL METHODS FOR SEDIMENT TRAPPING EFFICIENCY

The sediment trapping efficiency is a numerical value that theoretically varies between 0 and 1. According to van Rijn (2013), for large reservoirs, calculated as a single compartment, where the relationship between the length and the average depth (L/h) > 500, their values are normally limited between 0.90 and 1. However, when the reservoir is discretized in several n compartments, the ratio (L_n/h_n) decreases. This produces reductions in the sectorized values of E_n. This characteristic of the model provides distribution of deposits along the entire length of the reservoir, allowing the identification of more susceptible locations for silting. In the quantification of E_n, the SILTINGZ program uses classical methods synthesized in Table 2.

Table 2 – Empirical methods for trapping efficiency covered by SILTINGZ software

Method	Basic equations	
Churchill (1948)	$E^k{}_n = (-20+0.95 \cdot IS^{0,63})/(7100+IS^{0,63})$; $IS = Vol^k{}_n / ((Q^k{}_n)^2.L_n)$	(12)
Brune (1953)	$E^k{}_n = (0.00085+Ca^{1,1})/(0.0085+Ca^{1,1})$ (for $Ca \geq 0.007$); $E^k{}_n = (23.5750907 \cdot \ln(Ca)+151.179568)/100$ (for $0 \leq Ca < 0.007$); $Ca = Vol^k{}_n / Qm_n$	(13)
Heineman (1981)	$E^k{}_n = 0$ (for $Ca < 0.03$); $E^k{}_n = (-22+119.6 \cdot Ca/(0.012+1.02 \cdot Ca))/100$ (for $0.003 \leq Ca < 0.7$); $E^k{}_n = (-0.0165889465 \cdot Ca^4+0.274317797 \cdot Ca^3 -1.83260819 \cdot Ca^2+6.32355372 \cdot Ca+90.2793866)/100$ (for $0.7 \leq Ca < 5$); $E^k{}_n = 1$ (for $Ca \geq 5$);	(14)
USDA-SCS (1983)	$E^k{}_n = 0.97$ (for $Ca \geq 1$); $E^k{}_n = (97 -1.275 \cdot \lvert \ln(Ca) \rvert^{2.47})/100$ (for $0.02 \leq Ca < 1$); $E^k{}_n = (128 -11.51 \cdot \lvert \ln(Ca) \rvert^{1.304})/100$ (for $Ca < 0.02$);	(15)

In the set of Equations (12) to (15), the trapping efficiency is calculated basically as a function of two parameters: the sedimentation index (IS) – for the Churchill method – and the capacity-inflow (Ca), for the other methods. Still in these equations, $Vol^k{}_n$ and L_n are, respectively, the volume and length of compartment n. $Q^k{}_n$ is the average monthly flow and Qm_n is the volume of water that flows into the compartment during the interval of one month. As the inflows suffer seasonal variations, the trapping efficiency ($E^k{}_n$) is changed monthly. Note that, due to the formation of deposits, water volumes in compartments ($Vol^k{}_n$) are gradually reduced.

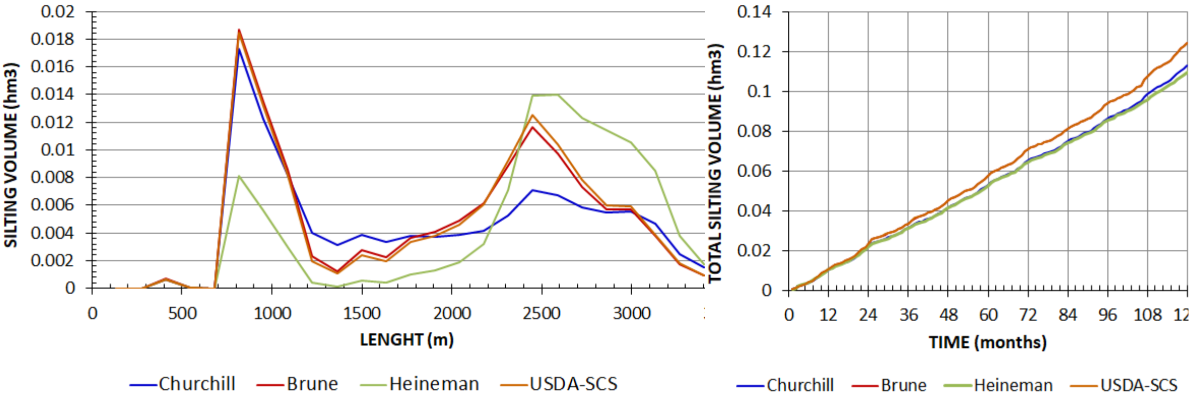
Garg and Jothiprakash (2008) point out that Brune's method is probably the most used for estimating sediment retention. This method was based on the monitoring of 44 reservoirs in the United States. The retention patterns obtained by Brune, Churchill and USDA-SCS are similar as the times of simulation increase. Heineman's method was based on the monitoring of

20 reservoirs, modifying Brune's equations for water bodies with flooded areas between 0.8 and 36.3 km^2 and volumes between 3000 and $4{\cdot}10^6$ m^3. For small reservoirs, sediment retention is less, so that Heineman's equations lead to lower silting rates than those of other methods.

RESULTS AND DISCUSSIONS

For the simulation, the rainfall historical series of the Fazenda Letreiro station, located near the Bom Jardim reservoir, was imposed. Thus, it is assumed that the same precipitation trend is maintained in relation to historical records. Figure 9 shows the silting results for a 10-year horizon, according to the application of the four methods covered by SILTINGZ.

Regarding to the most affected sites by the formation of deposits, it is noted that there are differences between the results, although the methods of Brune, Churchill and USDA-SCS indicate similar trends. In these cases, the main deposition zone is indicated upstream of the Bom Jardim stream delta (point RBJ), with predominant deposits in the larger compartments, in the vicinity of points E2 and D1. Heineman's method indicates that these last zones correspond to the main deposits, unlike the other methods. There are negligible deviations between Brune and USDA-SCS methods, indicating parity between the sediment trapping efficiencies estimated by both.


(a) Distribution of deposits along the axial length of the reservoir

(b) Time evolution of the total silted volume

Figure 9 – Estimated silting for 10 years

In relation to total silting, the highest deposition rates were verified by Brune and USDA-SCS methods (average value of 1040 m^3/month), whereas the Churchill and Heineman methods estimated rates of 944 m^3/month and 916 m^3/month, respectively. Considering the most extreme results and adopting a more palpable comparison, this suggests that the silting fills monthly volumes in the order of 40% of an olympic swimming pool, or volumes equivalent to 4.75 olympic swimming pools per year.

Simulations with longer periods allowed to identify changes in the reservoir bathymetric map. Figure 10 presents a set of maps for variable horizons from 10 to 75 years, simulated with the methods of Brune and Churchill. It is noted that, from times over 50 years, changes in the bed advance to the northern half of the reservoir.

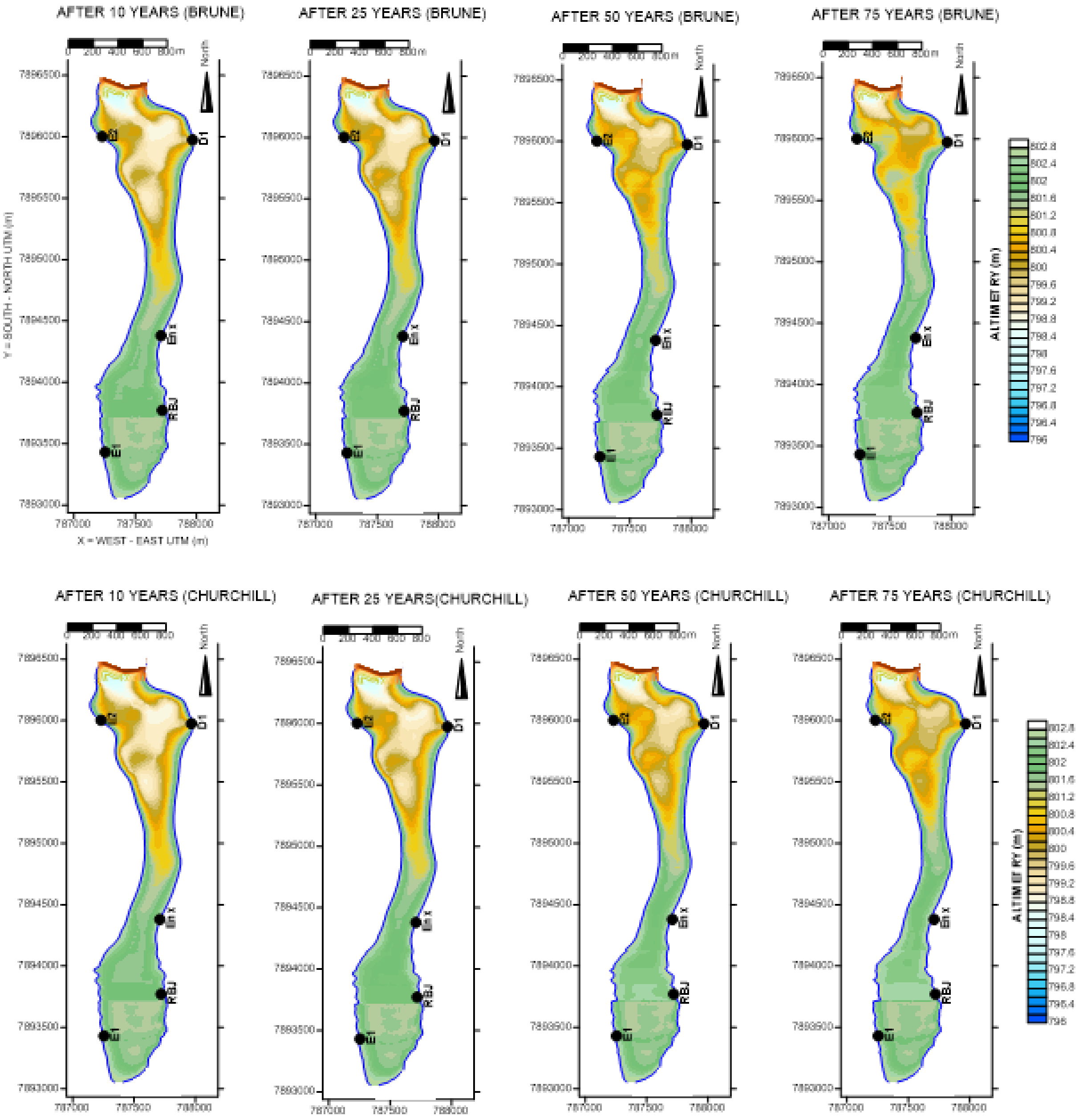


Figure 10 – Simulated bathymetric maps for periods of 10 to 75 years

Over time, the differences between the predictions of sedimentation by Brune's and Churchill's methods become apparent. Figure 11 shows differences between bed levels estimated by the Churchill method and the Brune method ($Z_{Churchill}$ - Z_{Brune}). Note that Churchill's method tends to calculate higher deposit heights after the injection of the main tributaries (RBJ and ENX) and in the narrow sections of the reservoir. Brune's method tends to provide more pronounced deposit heights in the northern half of the reservoir.

According to simulations, over the years silting becomes more evident at downstream from the RBJ delta. Considering fluctuations in the water level between altimetric levels of 802 and 803 m, there will be formation of latent sandbanks in this sector. The compartments most susceptible to the formation of sandbanks are shown at Figure 12. The sectors highlighted in brown refer to places where the depths become equal or less than 0.5 m.

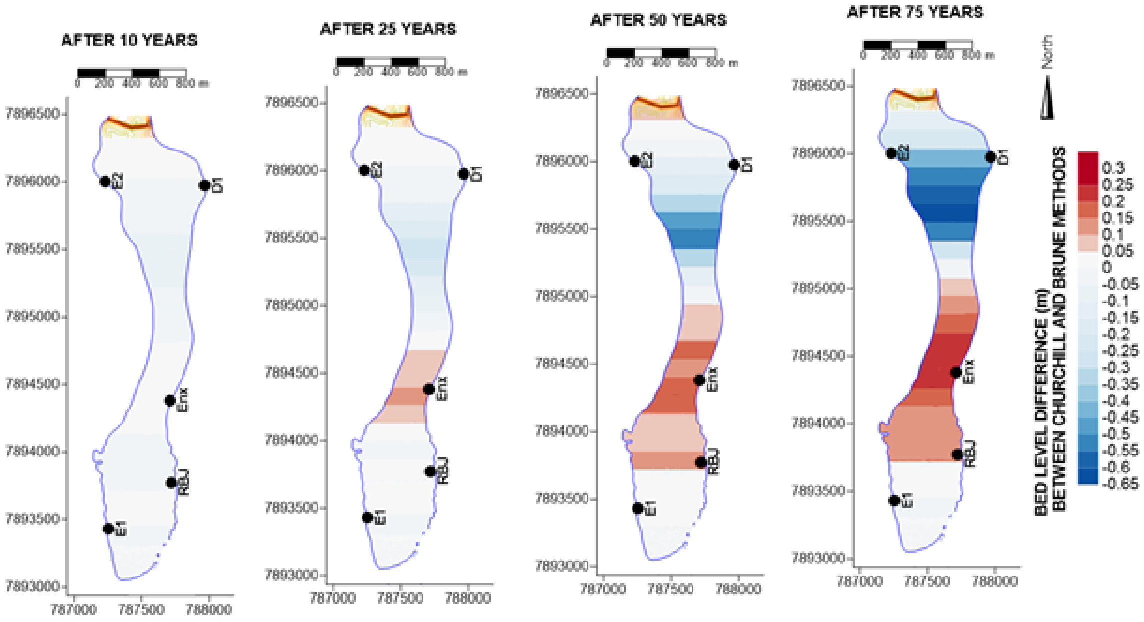


Figure 11 – Differences between bed levels simulated with Churchill and Brune methods

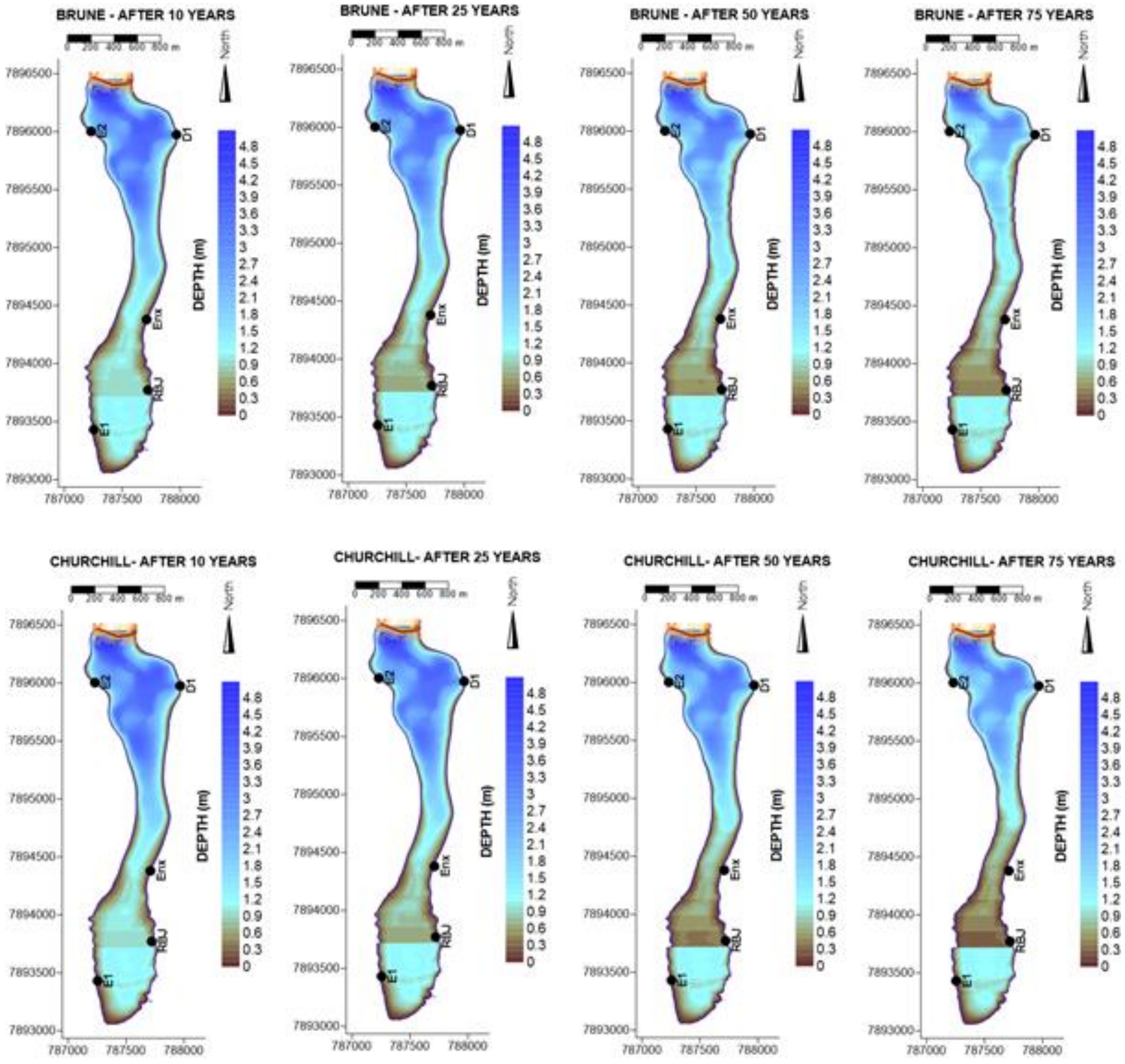


Figure 12 – Evolution of reservoir depth over the years

The longitudinal section of the reservoir (Figure 13) reveals that deposits formed immediately after the confluence of the RBJ tend to become prominent within a period of 50 years. This contributes to the formation of sandbanks in these sectors. The results also reveal that, for horizons over 50 years, silting tends to advance towards the northern half of the reservoir. Due to the greater retention efficiencies of these compartments, it is in these places where there is more accumulation of sediment.

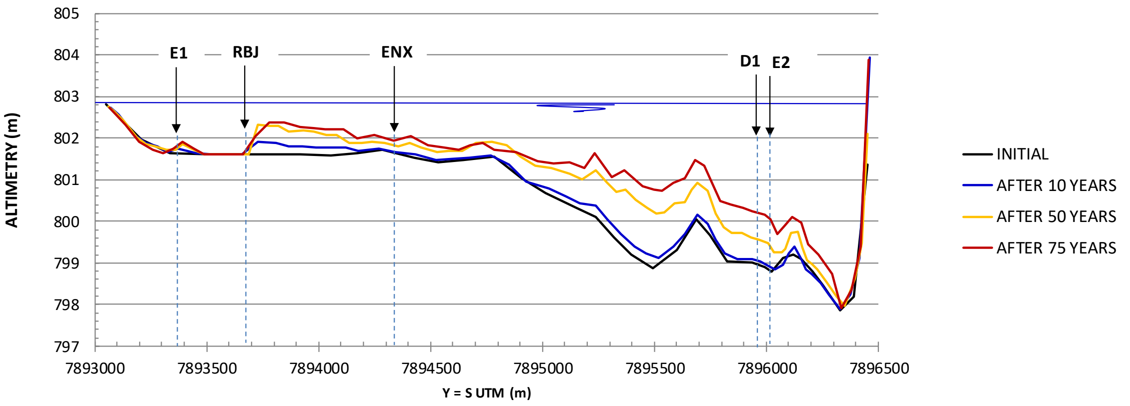


Figure 13 – Longitudinal section of the reservoir: silting evolution estimated by Brune method

It is important to remember that the Bom Jardim reservoir is used exclusively for public water supply. On the left edge of the dam there is a bypass channel, with depth of 2 m. This channel connects the reservoir to the pumping system responsible for carrying water to the treatment plant. According to the water level-volume curve of the reservoir, estimated by SILTINGZ, the dead volume, referring to quantities below the 801 m level, is about 0.7 hm^3. Below that level, the bypass channel could not be able to capture water. When maintaining the silting rates established here, the forecast is that the reservoir can have its useful volume affected from horizons of 56 to 64 years. After this interval, sediment deposits would have the potential to reach the base of the bypass channel, if no dredging operations are performed. According to the simulations, despite the sandbanks at downstream of RBJ and the distributed deposits, the Bom Jardim reservoir will operate with relative safety. This means that the water inlet of the bypass channel will not be blocked by sediment for at least 56 years. However, the removal of native vegetation by urbanization, agriculture and livestock may amplify the silting rates.

CONCLUSIONS

The Siltingz software is a predictor of reservoir silting, based on quantification of the sediment trapping efficiency. The discretization of the reservoir in compartments provides quick estimates of the preferred zones of deposit formation and, in more extreme cases, of possible sandbanks. Previous regional studies should be carried out in order to quantify synthetic series of affluent flows and key sediment curves. The presented regionalization methodology allows the generation of synthetic series of average monthly flows. In this context, monthly rainfall and watershed area are the independent variables. It is a viable technique with regard to the availability of fluviometric and pluviometric data and maps where contribution areas can be surveyed. Its potential for application in practical silting studies is evidenced by the availability of historical rainfall and flow records in electronic portals such as Hidroweb, for example.

Applications for the Bom Jardim reservoir, based on four methods of trapping efficiency, revealed monthly silting rates between 916 m^3/month and 1040 m^3/month and the latent possibility of sandbanks immediately downstream of the main point of discharge – delta of Bom Jardim stream. This would be equivalent to a loss of volume between 4 and 5 olympic swimming pools per year, which would be filled by bottom sediments. Despite this, the loss of the dead volume is more worrying, since the useful volume of the reservoir, which is used exclusively for public supply, can be gradually affected after a period of 56 to 64 years. This predictive study considered stationary conditions in the target basins. Obviously, these silting rates can be amplified with deforestation or delayed by reforestation in these watersheds.

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