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Technical Article

Influence of sediment distribution on the relationships among reservoir yield, spill, and evaporation losses

Influência da distribuição de sedimentos nas relações entre vazão regularizada, sangria e perdas por evaporação em reservatórios

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ABSTRACT

This study shows how the sedimentation process in reservoirs affects the yield–spill–evaporation losses in reservoirs of Ceará State, Brazilian Northeast. Reservoirs are assumed to have, initially, inverted conical shape. Three forms of sedimentation were investigated: type 1, with deposition occurring parallel to the wetted perimeter; type 2, deposition distributed proportionally to the water depth; and, type 3, deposition concentrated in the reservoir bottom. These sedimentation patterns were found in many reservoirs in Ceará, with capacity ranging from about 0.5 to 100 hm^3. Nevertheless, type 2 pattern was the most frequent. In this paper, five large reservoirs, over 100 hm^3, were studied using Monte Carlo approach, and considering the silting over the time horizon. It was found that sediment distribution can significantly affect the yield–spill–evaporation trade-off on large reservoirs. Type 1 results have the lowest impact on reservoir yield, followed by type 2 and type 3. For Cedro reservoir, the yield would go to zero in 2115, assuming a type 3 deposition pattern. These results reinforce the need for monitoring sedimentation in large reservoirs in the Brazilian semiarid region. In addition, this study provides a relatively simple methodology to predict the impact of siltation on reservoir yield-spill-evaporation relationships, for the three most found patterns of sedimentation.

Keywords: reservoir; sedimentation; water resources planning; yield.

RESUMO

Este estudo mostra como o processo de sedimentação em reservatórios afeta o balanço entre vazão regularizada, sangria e perdas por evaporação em reservatórios do estado do Ceará. Presume-se que os reservatórios tenham, inicialmente, forma cônica invertida. Foram investigadas três formas de sedimentação: tipo 1, com deposição paralela ao perímetro molhado; tipo 2, com deposição distribuída proporcionalmente à profundidade da água; e tipo 3, com deposição concentrada no fundo do reservatório. Esses padrões de sedimentação foram encontrados em diversos reservatórios do Ceará, com capacidades de aproximadamente 0,5 a 100 hm^3. No entanto, o padrão tipo 2 foi o mais frequente. Neste trabalho, foram estudados cinco grandes reservatórios, com capacidades superiores a 100 hm^3, utilizando-se a abordagem de Monte Carlo e levando em conta o assoreamento ao longo do horizonte temporal. Verificou-se que a distribuição de sedimentos pode afetar significativamente o balanço entre vazão regularizada, sangria e perdas por evaporação em grandes reservatórios. Os resultados para o padrão tipo 1 têm menor impacto sobre a vazão regularizada do reservatório, seguido dos tipos 2 e 3. Para o reservatório Cedro, a vazão regularizada seria zero em 2115, assumindo um padrão de deposição tipo 3. Esses resultados reforçam a necessidade de monitoramento do assoreamento em grandes reservatórios do semiárido brasileiro. Além disso, este estudo fornece uma metodologia relativamente simples para prever o impacto do assoreamento na relação entre vazão regularizada, sangria e perdas por evaporação, para os três padrões de sedimentação mais comumente encontrados.

Palavras-chave: reservatório; sedimentação; planejamento de recursos hídricos; vazão regularizada.

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INTRODUCTION

The Northeastern region of Brazil has a population of approximately 50 million inhabitants, and has an important infrastructure for the accumulation and distribution of water resources due to a drought-fighting policy implemented throughout the twentieth century (MALVEIRA; ARAÚJO; GÜNTNER, 2012). Currently, it is estimated that only the State of Ceará, focus of this study, has nearly 25 thousand dams, with a total water storage capacity close to 20 billion cubic meters (CAMPOS *et al.*, 2016). These reservoirs are the main source of fresh water for most of Ceará's inhabitants. However, reservoir siltation can significantly reduce their regulation capacity due to increased evaporation and spill losses (ARAÚJO; GÜNTNER; BRONSTERT, 2006). For water management purposes, knowing the impacts of sedimentation on the water yield is a major challenge.

Reservoir sedimentation is evaluated from field measurements to numerical modeling (MORRIS; ANNANDALE; HOTCHKISS, 2008, MUELLER *et al.*, 2010). For areas with multiple reservoirs randomly distributed along the river basin, such as the Brazilian Northeast, simplified models are necessary. Lima Neto, Wiegand and Araújo (2011), for example, investigated sediment distribution in a 25,000 km^2 basin with more than 4,000 surface reservoirs, with capacities ranging from 0.51 to 1,940 hm^3. The authors proposed an empirical equation, based on rainfall erosivity data, initial reservoir capacity, and sediment density, to estimate the changes in reservoir capacity due to silting. More recently, Negreiros and Lima Neto (2014) proposed simpler empirical relationships to predict reservoir silting in Brazilian reservoirs, also including non-semiarid areas.

Yang (2006) states that sediments can be deposited in the reservoirs following different patterns: uniform or non-uniform distribution along the wetted perimeter, or filling the lake bottom. Field studies by Araújo (2003) and Lima Neto, Wiegand and Araújo (2011) suggest that these three depositions forms have occurred in Ceará' s reservoirs.

Many studies, such as those by Borland and Miller (1958), Strand and Pemberton (1987), Mohammadzadeh-Habili *et al.* (2009), and Mohammadzadeh-Habili and Heidarpour (2010), have proposed complex shapes for describing the reservoir's deposition. Alternatively, more sophisticated approaches, such as 2D or 3D simulations, have been carried out to predict sediment distribution within the lake bottom (MAMEDE, 2008; GARCIA & GONÇALVES, 2011). However, only a few studies, such as those by Araújo (2003) and Araújo, Güntner and Bronstert (2006) focused on the impact of sedimentation on reservoir yield.

The simple inverted conical shape described by Campos (2010) has been largely applied for studying the relationships among reservoir yield, spill and evaporation in the Brazilian Northeast, and derivations from this original form could be potentially used to describe the impact of sedimentation on reservoir operation. The use of this simplification would be beneficial, as the reservoir yield error obtained by considering the conical shape and the real height-volume curve is lower than 4% of the mean annual inflow (CAMPOS *et al.*, 2016). Additionally, several reservoirs in the Brazilian Northeast do not present an updated height-volume curve, so that estimates of maximum water depth and volume could be used instead for the application of the inverted conical shape method.

The present study adapted the three patterns of silting proposed by Yang (2006) to the inverted conical shape proposed by Campos (2010) to investigate the impact of sediment distribution on the yield-spill-evaporation relationships of large reservoirs (up to about 2,000 hm^3) over the time horizon. The main contribution is the development of a simple methodology to evaluate how the reservoir's yield is reduced over time, and how this reduction is transferred to spill and evaporation losses. Note that this study is different from that of Araújo, Güntner and Bronstert (2006), in which the yield reduction due to sedimentation was evaluated using the real topo-bathymetries of small reservoirs of up to about 100 hm^3.

STUDY AREA AND METHODS

The study involves five large reservoirs of the State of Ceará (Figure 1), namely: Cedro, Pedras Brancas, Fogareiro, Orós, and Banabuiú, as detailed in Table 1.

The original storage vs. area vs. water depth relationship was obtained for each of these reservoirs. Among them, Cedro is the only reservoir that has had a topographic study carried out in 2000, that is,

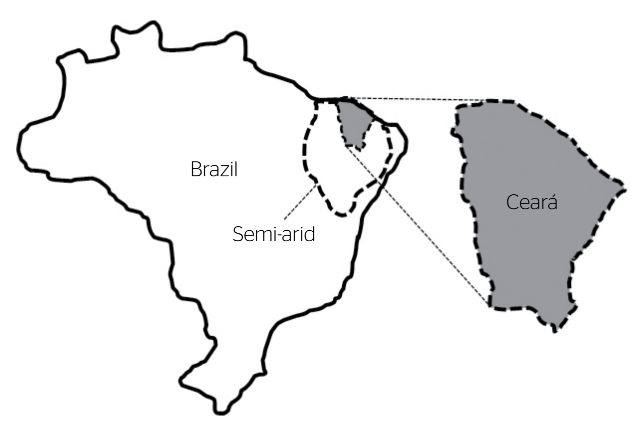

Figure 1 – The State of Ceará in the Brazilian semiarid region.

Table 1 – Characteristics of the selected reservoirs.

Reservoir	Construction date	Initial storage capacity (hm^3)	Maximum height (m)
Cedro	1906	126	18.5
Orós	1961	1,940	39.5
Banabuiú	1966	1,601	55.0
Pedras Brancas	1978	434	27.0
Fogareiro	1996	119	31.2

94 years after its construction. Note that topographic surveys are common in semiarid reservoirs, as many of these artificial lakes become completely empty during the drought periods.

The inflow and climatic data for all reservoirs were collected from the Water Resources Planning of the Jaguaribe River Basin (COGERH, 2000). That represents the most consistent set of data for these reservoirs.

As most reservoirs in Ceará, these five reservoirs were classified as convex or slightly convex, according to the morphometric shapes proposed by Håkanson's (1981). Campos *et al.* (2016) showed that the inverted cone described by Equation 1 fits very well the volume *vs.* height curves for these two classes of reservoirs, regarding the estimation of water yield (mean error lower than 1.5%):

$$V = \alpha h^3 \quad (1)$$

In which:

V = the reservoir storage at height h;

α = the reservoir shape factor;

h = the water height from the bottom.

Sediment retention

To estimate reservoir volume changes due to silting, the Equation 2, proposed by Lima Neto, Wiegand and Araújo (2011), was used:

$$\Delta V = \frac{V_o}{\rho} \xi \Sigma R \quad (2)$$

In which:

ΔV = the reservoir's capacity reduced by silting (hm^3);

V_o = the reservoir's initial volume;

ρ = the dry sediment bulk density (t/m^3);

ξ = the sediment retention rate ($t.m^{-3}.MJ^{-1}.mm^{-1}.ha.h$);

ΣR = the erosivity factor of the cumulative rain ($MJ\ mm\ ha^{-1}.\ h^{-1}$).

The rainfall erosivity was obtained by applying the Equation 3, by Bertoni and Lombardi Neto (1990):

$$R_m = 67.355\left(\frac{P_m^2}{P}\right)^{0.85} ;\ R = \sum_{m=1}^{12} R_m \quad (3)$$

In which:

R = the annual rainfall erosivity ($MJ.mm.ha^{-1}\ h^{-1}$);

P_m = the total monthly precipitation;

P = the mean annual precipitation (mm).

The erosivity factor of cumulative rain for each reservoir was calculated by Equation 3, using the reservoir's initial volume, and assuming a sediment retention rate ξ=3.65 x 10^{-7} $t.m^{-3}.MJ^{-1}.mm^{-1}.ha.h$, and an average dry sediment bulk density ρ=1.30 t/m^3 (LIMA NETO; WIEGAND; ARAÚJO, 2011). Equation 2 was used to calculate the volume of sediment deposited in each reservoir by decade. Thus, it was possible to estimate the reservoirs' capacity in 2015 and predict future scenarios (50 and 100 years).

Reservoir's shape and sedimentation pattern

For each reservoir, four height-volume curves were built based on the conical shape approximation. This shape fits well most reservoirs in Ceará and is considered appropriate for estimating the reservoir's relationships of yield-spill-evaporation losses (CAMPOS, 2010).

The reservoir's original shape considers the volume vs. height curve described by Equation 1. The three reservoirs' shapes after siltation (see Figure 2) consider different forms of sediment deposition:

- Type 1, the sediments occur parallel to the wetted perimeter;
- Type 2, the sediment layer is proportional to the water depth;
- Type 3, the sediments concentrate at the bottom of the reservoir.

Note that these forms of deposition are simplifications of the patterns observed by Yang (2006), Araújo (2003), and Lima Neto, Wiegand and Araújo (2011).

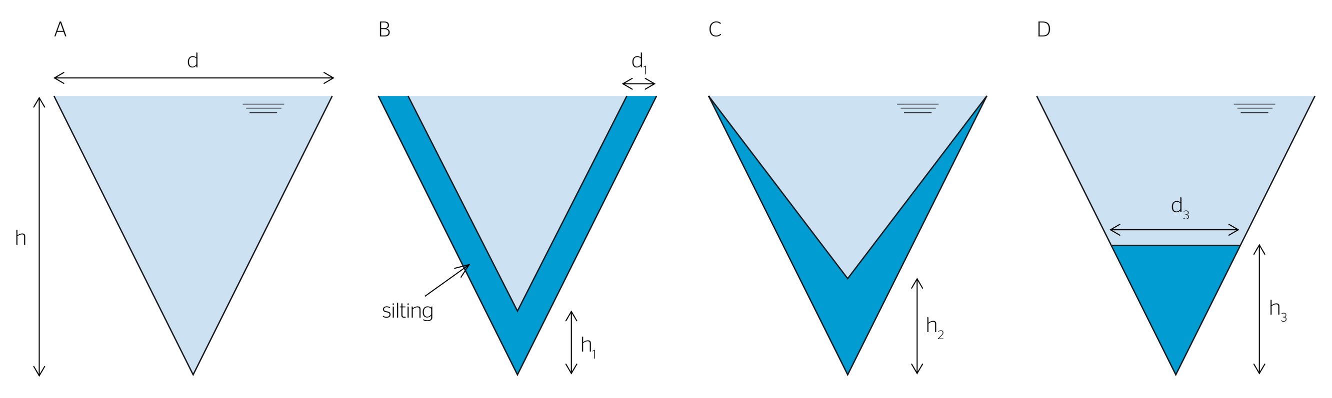

Figure 2 – Conical reservoir model (A), and possible forms of sediment distribution: deposition occurring parallel to the wetted perimeter — Type 1 (B), proportionally to the water depth — Type 2 (C), and concentrating at the bottom of the reservoir — Type 3 (D).

Thus, sediment deposition ΔV is calculated by Equation 2, and the volume of the reservoirs for each time scenario is determined by the Equation 4:

$$V = V_o - \Delta V \quad (4)$$

In which:

The initial volume = $V_o = \pi d^2 h/12$ (see Equation 1).

The variables h_1, d_1, d_2, h_3, and d_3 (see Figure 2), as well as the height-volume curves, for each time scenario, can be determined from the Equations 5, 6 and 7:

$$\text{Type 1: } V = \frac{\pi\left(d - d_1\right)^2\left(h - h_1\right)}{12} \quad (5)$$

$$\text{Type 2: } V = \frac{\pi d^2\left(h - h_2\right)}{12} \quad (6)$$

$$\text{Type 3: } V = \frac{\pi d_3^2 h_3}{12}, \text{ where } \frac{d_3}{h_3} = \frac{d}{h} \quad (7)$$

Reservoir's yield estimation

The reservoir's relationships of yield-spill-evaporation losses were calculated by solving the reservoir's water budget given by Equation 8. Some basic assumptions were made, namely: time step is one month; water released from the reservoir is constant over months; the net evaporation (evaporation minus precipitation) varies over the months but is constant over the years; the reservoir's yield is computed for steady-state conditions, to eliminate the effect of the reservoir's initial storage assumption.

$$V_{i+1} = V_i + (P_i - E_i)\,(A_{i+1} + A_i)/2 + I_i - R_i - S_i \quad (8)$$

In which:

V_{i+1} and V_i = the water volumes in the reservoir in months i + 1 and i, respectively;

P_i = the average rainfall over the reservoir lake in month i;

E_i = the average depth of water evaporated from the lake's surface in month i;

A_{i+1} and A_i = the area of the reservoir lake in months i + 1 and i, respectively;

I_i = the reservoir inflow volume in month i;

R_i = the total reservoir withdrawals in month i;

S_i = the water volume lost by the spillway.

For 90% reliability, used in this study, the yield (Q) is equal to the mean annual net withdraw divided by 0.95.

Monte Carlo Simulation

Monte Carlo simulation has been largely applied to solve stochastic hydrology problems since its origin in 1950. In reservoir storage analysis, many authors have made important contributions, such as: Chow (1951), Thomas and Fiering (1962), Fiering (1967), Salas and Yevjevich (1972), Klemes (1987), and Kuria and Vogel (2015).

In this study, reservoir analysis using Monte Carlo simulation is performed as described by Campos, Souza Filho e Lima (2014), in which stochastic hydrology tools and a reservoir simulation operation were used to estimate the variability of the water yield, spill and evaporation losses for each reservoir by using a FORTRAN code. The methodology has seven steps:

- Collecting the monthly reservoir inflow data (from COGERH, 2000);
- Estimating the statistical parameters of annual inflows;
- Fitting the annual inflow data to gamma probability density function, in which the inflows were assumed to be serially uncorrelated;
- Generating synthetic long term series for annual inflows (at least 80 years of data);
- Fragmenting annual inflows in a monthly basis, using the Svanidze (1980) method;
- Solving the reservoir budget (Equation 8) for a given reliability (90% in this study) by using the synthetic monthly stream flow series and the average losses of the lake (evaporation minus precipitation);
- Estimating, in steady-state conditions, the expected values of reservoir yield, evaporation and spill losses. The computational effort involved in the simulations was not significant: a few seconds for each run.

RESULTS AND DISCUSSION

This section shows the results of silting and changes in yield-spill-evaporation losses for the three forms of deposition and for the current and future scenarios. Since Cedro is the only one of the five selected reservoirs with topographic surveys over a long period after its construction, specific evaluations were carried out for it.

Erosivity estimations

Sediment deposition was estimated from Equation 2. Thus, knowing the data of original capacity (V_o), dry sediment bulk density (ρ), and sediment retention rate (ξ), the only parameter remaining for estimating the volume reduction due to siltation (ΔV) is the erosivity factor of the cumulative rain (ΣR). As an example, Figure 3 shows the evolution of the rainfall erosivity R for the Cedro reservoir. It is observed that the values fluctuate around a stationary mean (6,197 $\text{MJ.mm.ha}^{-1}.\text{h}^{-1}$), with the same behavior occurring for the other reservoirs. Thus, it was assumed that the mean erosivity can be used as a reference to estimate the silting of the five selected reservoirs over the years.

Fitting observed and theoretical changes in Cedro reservoir's storage vs. height curves

The impact of the types of sediment deposition on the height-volume curves of Cedro reservoir are shown in Figure 4. The topographic surveys of 1906 and 2000, obtained from Araújo (2003), are used as a reference. As already mentioned, topographic surveys are common in semiarid reservoirs, as they usually become empty during droughts. In the case of Cedro reservoir, a topographic study was conducted (instead of a bathymetric survey) because the lake had a volume of less than 1% of its capacity in April 2000.

An excellent fit of the conical model to the height-volume curve of 1906 was observed, with a coefficient of determination $r^2=0.999$ (see Figure 4). This corroborates the results of Campos *et al.* (2016), which suggest that the inverted conical shape generates good results in reservoir simulation.

Equation 2 resulted in a siltation value (DV) that was very close to the value obtained from the topographic survey for Cedro reservoir. Therefore, this equation was considered adequate to predict siltation scenarios at a planning level.

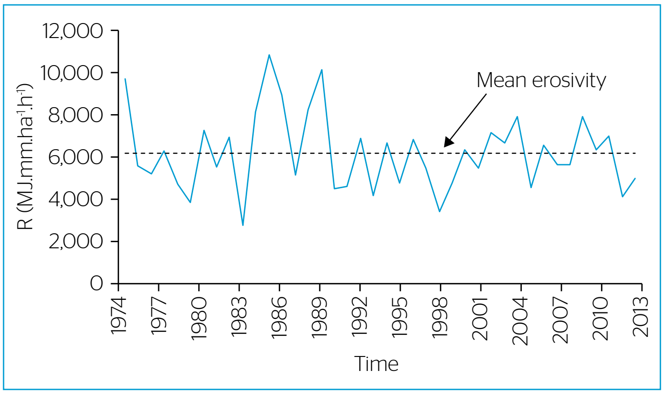

Figure 3 – Temporal evolution of rainfall erosivity for the Cedro reservoir.

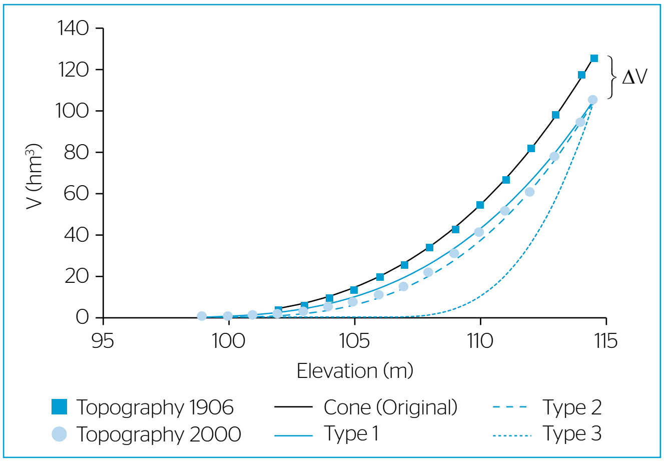

Figure 4 – Simulation of the impact of siltation (V) and its different forms of sediment distribution (type 1, type 2 and type 3) on the height-volume curves of the Cedro reservoir. The topographies of 1906 and 2000 were obtained by Araújo (2003).

After fitting the three different sediment deposition models to the topography, the values obtained were $r^2=0.998$, 0.999 and 0.948 for type 1, type 2 and type 3, respectively. Therefore, considering the r^2 metrics, it can be inferred that the type 2 model best represented the sediment distribution in the Cedro reservoir. Note that sediment distribution in 66.7% of the reservoirs studied by Araújo (2003) were also best represented by type 2, while the other models – type 1 and type 3 – represented 16.7% of the reservoirs each.

Changes in the reservoirs' storage vs. height curves

Although no direct measurements of silting are available for the other reservoirs, the study by Lima Neto, Wiegand and Araújo (2011) provided an estimate of ΔV for the Orós reservoir, which was only 20% lower than that obtained with Equation 2. A summary of the results of silting for the selected reservoirs is shown in Table 2. The annual reduction of reservoir's capacity, related to its initial volume, ranged from 0.15 to 0.20%. These values are close to those found by Araújo (2003) for small reservoirs in the State of Ceará. This result is also consistent with those of Lima Neto, Wiegand and Araújo (2011), who reported similar silting rates from small to large dams in the Upper Jaguaribe Basin in Ceará. On the other hand, the sedimentation rates found here are significantly lower than those reported in the literature for USA, which are of the order of 1% per year (YANG, 2006; MORRIS; ANNANDALE; HOTCHKISS, 2008). This is attributed to the effect of the dense reservoir networks present in the Brazilian Northeast, in contrast to the sparser reservoir networks in the USA.

Figure 5 illustrates the impact of the three patterns of sediment distribution on yield-spill-evaporation losses for Cedro reservoir. Depending on the sediment distribution model, the values of evaporation, spill, and yield may vary significantly. As the type 1 model takes up smaller a surface area than the original form (see Figure 2B), evaporation losses are lower (within 20%) and slightly decreased over the time horizon. Since the type 2 model takes up the same surface area (see Figure 2C), the results of evaporation losses are practically invariable. Finally, the type 3 model tends to maintain the water surface at higher levels (see Figure 2C), resulting in larger surface areas than the other types and, consequently, promoting higher evaporation losses than the original

Table 2 – Prediction of reservoir volumes (V) over time and siltation rates.

Reservoir	V_o (hm³)	V (hm³)			$(\Delta V/V_o)/\Delta t$ (%/year)
		2015	2065	2115	
Cedro	126	102	91	80	0.17
Orós	1,940	1,746	1,566	1,386	0.15
Banabuiú	1,601	1,478	1,352	1,225	0.20
Pedras Brancas	434	409	375	340	0.16
Fogareiro	119	115	106	96	0.15

shape (within 84%), which slightly increases over time. These results are consistent with those of Araújo, Güntner and Bronstert (2006), which reported evaporation losses either lower or higher than the original ones for diverse reservoirs of Ceará. Differently from the present study, in which three different models of sediment deposition were assumed, Araújo, Güntner and Bronstert (2006) evaluated the yield reduction due to sedimentation by using the real topo-bathymetries of the reservoirs. Moreover, their study was limited to reservoirs of up to about 100 hm³. Therefore, the results obtained here suggest that type 1, type 2, and type 3 models are potentially representing sediment distribution in reservoirs of different shapes and sizes.

On the other hand, because of silting, Figure 5 shows that spill losses are up to 85% higher than the original, with the major impacts observed for the type 1 model, followed by type 2 and type 3. Note that these spill losses increase over the years for the three sediment distribution models. Because of the combined effects of evaporation and spill, the reservoir yield is reduced in comparison to the original situation by 6, 26, and 100% for type 1, type 2 and type 3 models, respectively. As expected, the regulated flow also decreases with sedimentation, i.e. over the time scenarios.

Figure 6 shows an overall assessment of the impact of the sediment distribution model on the water yield Q of the selected reservoirs for

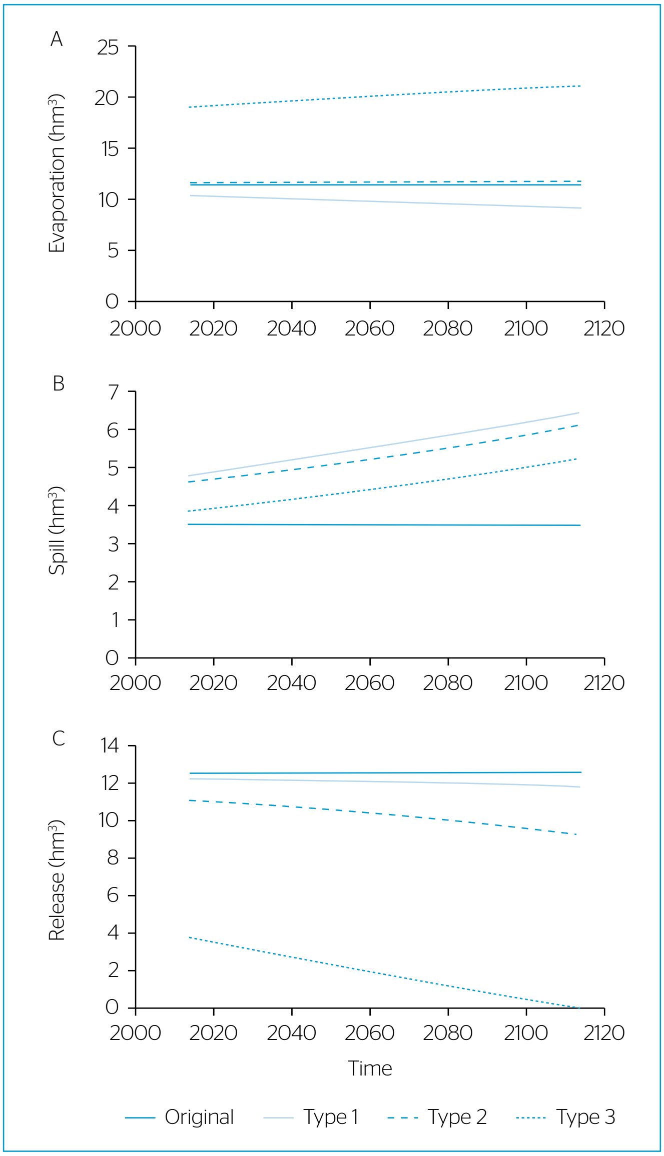

Figure 5 – Water balance simulation for the Cedro reservoir for the different forms of sediment distribution (type 1, type 2 and type 3): (A) evaporation; (B) spill; (C) release.

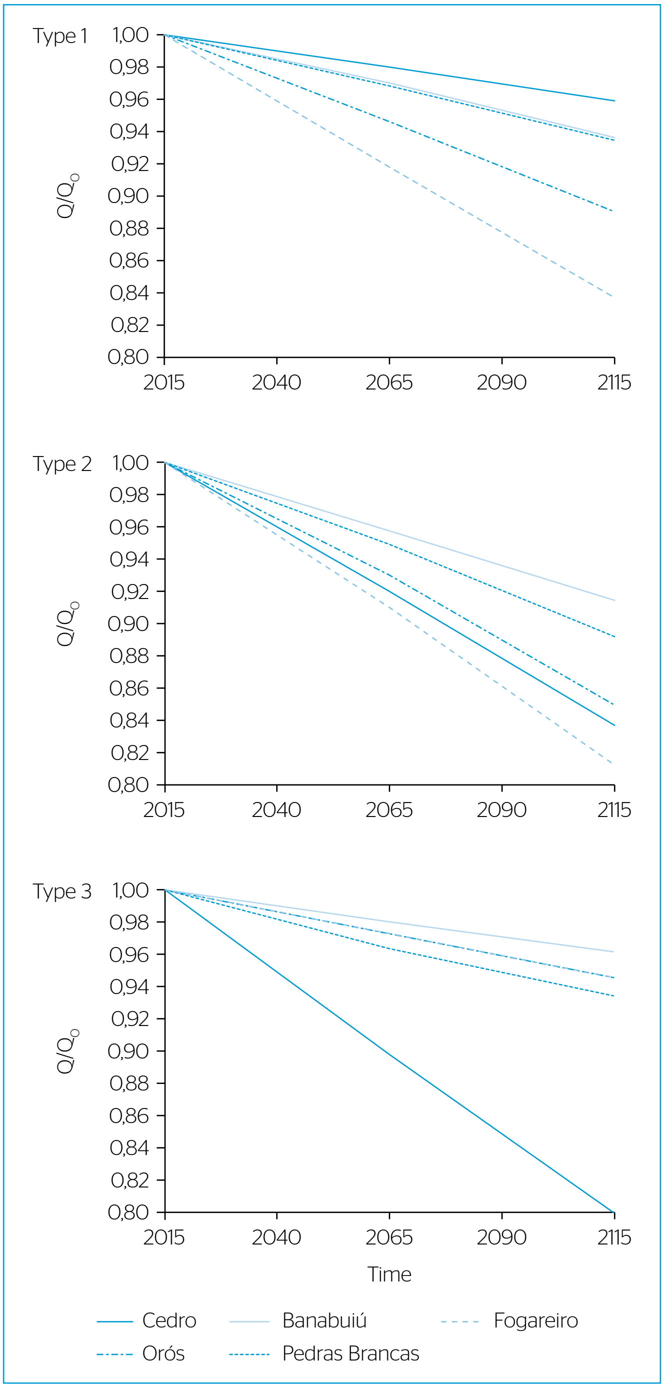

Figure 6 – Simulation of the impact of the sediment distribution model (type 1, type 2 and type 3) on the water yield of the selected reservoirs.

each time horizon, as compared to the initial water yield Q_o (reference year: 2015). It is seen for all reservoirs in which type 1, type 2 and type 3 models present, in that order, an increasing decline in the Q/Q_o ratio over time. For example, for Pedras Brancas reservoir, the Q/Q_o ratios in 2015 are 0.93, 0.89, and 0.67 for type 1, type 2 and type 3 models, respectively. In summary, the type 1 model provides yield reductions ranging from 4–16% of the initial yield, while type 2 and type 3 models provide respectively reductions of 9–19 and 19–100%. This confirms the significant impact of the sediment distribution model on reservoir yield and suggests that the different forms of sediment deposition can be assumed for diverse scenarios (optimistic, intermediate and pessimistic), to evaluate the effect of silting on water availability.

It is also interesting to compare our results with previous studies. In the present study (see Figure 6), the type 2 model provided a yield reduction rate of about 0.16% per year for the Cedro reservoir. This value is very close to that (0.15% per year) obtained by Araújo, Güntner and Bronstert (2006). This gives credence to the methods employed herein. On the other hand, the average yield reduction rate obtained in the present study (large reservoirs) was about 0.14% per year, while the reduction rate reported by Araújo, Güntner and Bronstert (2006) (small reservoirs) was about 0.25% per year. This suggests that water yield declines more rapidly in smaller reservoirs than in large reservoirs. To interpret the results in a more systematic way, the yield–volume elasticity, which represents the relative impact of yield reduction with respect to volume reduction over time (see ARAÚJO; GÜNTNER; BRONSTERT, 2006), was also analyzed here. While our average yield–volume elasticity was about 0.85, Araújo, Güntner and Bronstert (2006) reported the average value of 0.80. Although the difference is not significant, this result confirms that, also in relative terms, the water yield reduces more rapidly in smaller reservoirs.

CONCLUSIONS

In this paper, we analyzed the influence of sediment distribution on the water balance of five strategic reservoirs (126–1,940 hm^3) in the State of Ceará, Northeastern Brazil. A conical shape approximation was used to describe the height-volume curves of the reservoirs. Additionally, three possible different forms of sediment distribution were also investigated: deposition occurring parallel to the wetted perimeter (type 1), proportionally to the water depth (type 2), and concentrating at the bottom of the reservoir (type 3). The present study contrasts with previous studies available in the literature, in which the yield reduction due to sedimentation was evaluated by using the real topo-bathymetries of small reservoirs of up to about 100 hm^3. The results indicated that the type 2 model best represented the sediment distribution in small reservoirs. Simulations were performed for larger reservoirs (without topo-bathymetry) using the Monte Carlo method and considering the three different models for sediment distribution. It was found that sediment distribution can significantly affect the water yield, with the deposition of type 1 resulting in higher yield, followed by type 2 and type 3. This suggests that topo-bathymetric surveys in such larger reservoirs are of utmost importance to identify their sediment distribution patterns. Additionally, the present study provides a methodology for predicting the impact of siltation on reservoir yield, following different scenarios: optimistic (type 1), intermediate (type 2), or pessimistic (type 3). Finally, the results support that idea that both in absolute and relative terms, silting impacts water yield more significantly in small reservoirs than in large ones.

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