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INCREASE IN WATER-SCARCITY RISK IN A BRAZILIAN DRY-REGION RESERVOIR[1]

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ABSTRACT - This study assesses the extent to which silting increases water-scarcity risk, considering the temporal reduction of water availability and increased demand using land use and water-demand scenarios at the transition of Caatinga and Cerrado biomes of the Bocaina reservoir watershed ($10^2 hm^3$), in the Brazilian dry region. Methodological steps were: reservoir silting measured in-situ 20 years after dam construction; climate variables computed with the aid of a conventional station (2005–2014); soil erodibility assessed using 16 soil samples; and topography and land cover estimated based on 21 years of Landsat imagery. Three land use scenarios were generated (invariability, degradation and preservation) with the climate scenario derived from the semi-arid rainfall temporal variability; whereas two water-demand scenarios (invariability and higher efficiency) were a function of the efficiency of the irrigation systems. Water availability was calculated using the volume-yield elasticity (VYELAS) Model. The field results (1985–2015) showed a gross erosion rate of 13.5 $Mg \cdot ha^{-1} \cdot yr^{-1}$ in the basin. The annual sediment yield (1.7 $Mg \cdot ha^{-1}$) and the decadal reservoir silting (1.0%) were below regional average due to the low sediment delivery ratio (12.6%) in the area. Scenario projections (2040) suggest water demand may double if irrigation methods do not improve, whereas siltation may cause water availability to decrease up to 10% in the period. In this case, the water-supply reliability will be below the recommended standard value (90%), regardless of the land use scenario. Nevertheless, simultaneous soil preservation and improved irrigation efficiency can reduce the decadal water-scarcity risk from 82% (worst scenario) to 17%.

Keywords: Caatinga biome. Cerrado biome. Water management. Water demand. Silting.

AUMENTO DO RISCO DE ESCASSEZ HÍDRICA EM UM RESERVATÓRIO DA REGIÃO SECA BRASILEIRA

RESUMO - Este estudo avalia como o assoreamento aumenta o risco de escassez hídrica, considerando simultaneamente redução temporal da disponibilidade hídrica e aumento da demanda utilizando cenários de uso da terra e demanda hídrica na transição dos biomas Caatinga - Cerrado da bacia do reservatório Bocaina (10^2 hm^3), na região seca brasileira. A metodologia seguida: assoreamento medido no reservatório 20 anos após a construção da barragem; variáveis climáticas obtidas de estação convencional (2005-2014); erodibilidade do solo avaliada usando 16 amostras de solo; topografia e cobertura do solo estimadas com base em 21 anos de imagens Landsat. Foram gerados: cenários de uso da terra (invariabilidade, degradação, preservação) com cenário climático derivado da variabilidade temporal da precipitação no Semi-árido; cenários de demanda hídrica (invariabilidade, maior eficiência), função da eficiência dos sistemas de irrigação utilizados. A disponibilidade hídrica calculada usando o Modelo VYELAS. Os resultados de campo (1985-2015) mostraram erosão bruta anual na bacia de 13,5 $Mg \cdot ha^{-1}$ com produção anual de sedimentos (1,7 $Mg \cdot ha^{-1}$) e assoreamento decadal do reservatório (1,0%) abaixo da média regional devido à baixa taxa de aporte de sedimentos (12,6%) na área. Os cenários projetados (2040) indicam demanda hídrica duplicando se os métodos de irrigação praticados não melhorarem e disponibilidade hídrica diminuindo (em até 10%), por assoreamento. Nesse caso, tem-se confiabilidade do suprimento hídrico abaixo do padrão recomendado (90%), independentemente do uso da terra. Todavia, a preservação do solo, simultaneamente com eficiência de irrigação melhorada, reduziria o risco decadal de escassez hídrica de 82% (pior cenário) para 17%.

Palavra-chave: Bioma Caatinga. Bioma Cerrado. Gestão hídrica. Demanda hídrica. Assoreamento.

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INTRODUCTION

In dry environments, the principal aim of surface reservoirs is to improve water availability. In the Brazilian dry northeastern region, surface reservoirs provide more than 90% of the water supply (GAISER et al., 2003). Reservoirs are prone to silting, which reduces their storage capacity and changes their morphology towards a more open shape. These alterations increase evaporation and water outflow and reduce water availability (ARAÚJO; GÜNTNER; BRONSTERT, 2006), which is particularly deleterious in water-scarce areas, such as in northeastern Brazil. Simultaneously, water demand expands with time and generates an increasingly unbalanced system. Better knowledge of silting impacts on reservoirs improves the efficiency of local water management, especially in water-scarce environments, where water grants should be judiciously conceded.

Araújo; Güntner; Bronstert (2006) investigated how reservoir silting reduces water availability and aggravates conflicts for water access (GAISER et al., 2003). The authors however did not consider land use or demand scenarios to assess the temporal evolution of the water balance. Including such variables represents an advance in understanding the impact of silting on water scarcity. In addition, it was not known whether the results obtained in the Caatinga could be extrapolated to other biomes. The study was performed in a meso-scale basin at the transition between the semi-arid Caatinga and the sub-humid Cerrado biomes where it is necessary to improve the water-management system because of local water conflicts. In order to justly solve such conflicts, decision makers must be able to accurately evaluate water availability (MARTON; KAPELAN, 2014), which changes over time.

Erosive processes increase with anthropogenic activities in a basin. At the Caatinga biome, especially in the rainy season, cutting vegetation for firewood and opening up areas for livestock and agriculture cause changes in hydrological and sedimentological behavior. Additionally, these anthropogenic activities affect infiltration patterns and produce silting in the reservoir. Thus, reducing water availability (ARAÚJO; GÜNTNER; BRONSTERT, 2006). In the Cerrado biome, which has intense land use (crop yield, burning, deforestation, mining), the accelerated expansion of anthropogenic activities contributes to serious environmental problems associated with soil degradation and water scarcity (HUNKE et al., 2015), such as high rates of reservoir silting (DURÃES; MELLO; BESKOW, 2016; DURÃES; COELHO FILHO; OLIVEIRA, 2016) and low water quality.

Hydrosedimentological studies in watersheds can be supported by computational models, but the required information is generally not available. The Universal Soil Loss Equation (USLE) is considered a reference model because of the ease of implementing the factors in a distributed way (including geo-processing) and the reliability of its results (BENAVIDEZ et al., 2018). Scenario analysis makes it possible to infer watershed behavior for possible situations of soil use and occupation, as well as conservation practices, without physically intervening in the environment. This study aimed to assess how reservoir silting increases the risk of water scarcity, while considering not only the continuous reduction of availability, but also a progressive increase in demand.

MATERIALS AND METHODS

The study area was the Bocaina Reservoir Basin (1,070 km²), located in the transition of the Caatinga and Cerrado biomes in the semi-arid region of Piauí (Figure 1). The average annual evaporation is 2,400 mm and the precipitation is 820 mm, concentrated between February and April. The Bocaina dam was built in 1985 on the intermittent Guaribas River, with initial capacity of 115 hm³. The reservoir has different uses, with water conflicts, particularly since 2012, due to a multi-annual drought (ARAÚJO; BRONSTERT, 2016). The conflicts occur among farmers cultivating the river margins near the reservoir and those cultivating downstream to enhance productivity, with the former demanding lower water release and the latter demanding higher. Intensive fish farming in the lake, a growing industry in Brazilian reservoirs, intensifies the conflicts because it demands a reduced release of water.

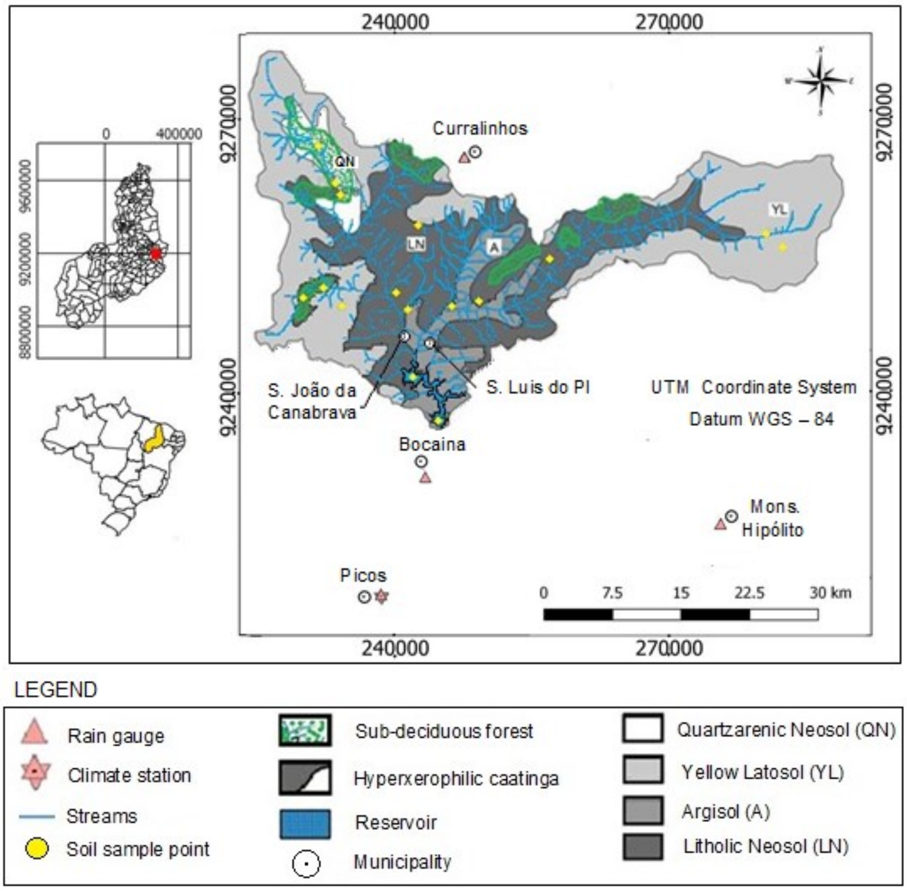

Figure 1. Location of the Bocaina basin, rain gauges and soil sample points.

In-situ assessment of the sediment yield: the sediment yield (SY) of the basin was estimated in Equation 1, where ΔM is the accumulated silted mass in the reservoir during the time interval (Δt, in years); A is the reservoir catchment area; and η is the reservoir trap efficiency, calculated according to Brune (1953). To assess the silting volume variation (ΔV), we used the bathymetric survey of the reservoir made in 2015 (PIAUÍ, 2016a). Together with the *in-situ* assessment of the respective dry bulk density (ρ), it was possible to estimate the silted mass. To calculate ρ, six sediment samples were taken from the reservoir flooded area.

Equation 2 was used to estimate the sediment delivery ratio (SDR), which was assumed constant for all scenarios. In Equations 2 and 3, ε corresponds to the annual gross erosion per unit area, computed according to Wischmeier and Smith (1978).

$$\mathrm{SY} = \frac{\Delta \mathrm{M}}{\Delta \mathrm{t.A.\eta}} = \frac{\Delta \mathrm{V.\rho}}{\Delta \mathrm{t.A.\eta}} \tag{1}$$

$$\mathrm{SDR} = \frac{\mathrm{SY}}{\varepsilon} \tag{2}$$

In Equation 3, R is the annual rainfall erosivity ($\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}}$); K is the soil erodibility ($\mathrm{Mg \cdot h \cdot MJ^{-1} \cdot mm^{-1}}$); L is the slope-length dimensionless factor; S is the slope-steepness dimensionless factor (L and S were represented as LS – dimensionless topographic factor); C is the land -cover dimensionless factor; and P is the dimensionless conservation-practice factor. The annual erosivity was calculated by the empirical Equation 4 (GAISER et al., 2003). In Equation 4, H_j is the total precipitation in the *j-th* month (mm) and $\overline{\mathrm{Ha}}$ is the long-term average annual precipitation (mm) with parameters (54.883 and 0.7141) calibrated by López-Gil (2017), using data from Picos INMET climate station (Figure 1) for the period 2005 – 2014. Equation 4 was used here because there were no data available to directly calculate the critical 30-min intensity. The erodibility factor was obtained by Equation 5, where the λ factors are parameters: λ_1 is the grain-size factor (Equation 6, where SIL is the silt content and CL the clay content); λ_2 is the soil dimensionless permeability factor (WISCHMEIER; SMITH, 1978); λ_3 is the average weighted particle smaller than 2 mm, given by Equation 7; and λ_4 is the ratio between organic matter and very fine sand contents: d_i corresponds to the i-*th* particle diameter (mm) and f_i to the frequency (%) of the diameter range between d_{i-1} and d_i. To compute the erodibility K factor, 16 soil samples were collected from the prevailing soils and analyzed (Figure 1).

The topographic factor (LS) was calculated using Equation 8, where S_0 is the terrain slope (%) and Lr is the slope length (m), while L_R is given by Equation 9 (GAISER et al, 2003), where ΣL_{dr} represents the total length of the drainage inside the analyzed area. The land-cover C factor was based on land use and land cover maps, after classification of the satellite images (Landsat 5) with 30 m spatial resolution. Satellite imagery was used from three dates (July/1989, July/2000 and August/2010) where it was possible to identify the five prevailing soil use classes in the basin: shrub vegetation, thinned vegetation, exposed soil, agricultural use and water (Figures 2a, 2b and 2c).

$$\varepsilon = \mathrm{R} \cdot \mathrm{K} \cdot \mathrm{L} \cdot \mathrm{S} \cdot \mathrm{C} \cdot \mathrm{P} \tag{3}$$

$$R = \sum_{j=1}^{12} 54.883 \cdot \left(\mathrm{H}_j^2 / \overline{\mathrm{Ha}}\right)^{0.7141} \tag{4}$$

$$\mathrm{K} = 7.48\mathrm{x}10^{-6} \cdot \lambda_1 + 4.48\mathrm{x}10^{-3} \cdot \lambda_2 - 6.312\mathrm{x}10^{-2} \cdot \lambda_3 + 1.0396\mathrm{x}10^{-2} \cdot \lambda_4 \tag{5}$$

$$\lambda_1 = \mathrm{SIL\%} \cdot (100 - \mathrm{CL\%}) \tag{6}$$

$$\lambda_3 = \mathrm{EXP}\left(\sum_i \mathrm{f_i} \cdot \mathrm{Ln}\left(\frac{\mathrm{d_i} + \mathrm{d_{i-1}}}{2}\right)\right) \tag{7}$$

$$\mathrm{L.S} = 9.84\mathrm{x}10^{-3} \cdot \mathrm{L_R}^{0.65} \cdot S_0^{1.18} \tag{8}$$

$$\mathrm{L_R} = \mathrm{A}/(4 \cdot \sum \mathrm{L_{dr}}) \tag{9}$$

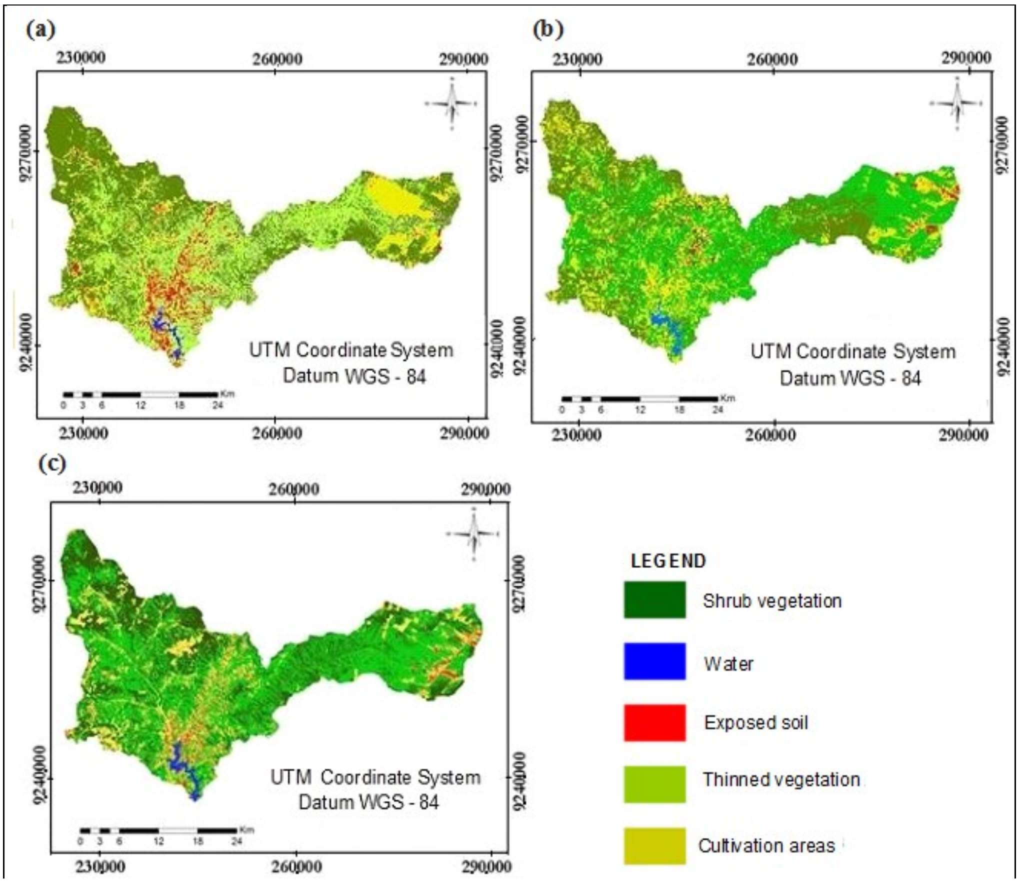

Figure 2. Land use-land cover in the Bocaina basin (a) year 1989, (b) year 2000, (c) year 2010

There was a ground-truthing campaign in June 2016 to identify land use in the catchment area of Bocaina dam. In terms of agriculture, the main crops were maize (*Zea mays*), beans (*Phaseolus vulgaris*) and manioc (*Manihot esculenta*), usually cultivated in association. The following was assumed: C = 0.039 for agriculture (LIMA et al., 2014), C = 0.017 for shrub vegetation and C = 0.006 for thinned vegetation (SANTOS et al., 2014). Furthermore we assumed P = 1 considering that in the area no conservation practice was identified.

Equation 3 was processed using map algebra with Landsat 5 images (30 m spatial resolution); the raster calculator tool of the ArcGis 9.3 and the surface digital model SRTM (Shuttle Radar Topographic Mission, 2000) at the 1:250 000 scale. In order to analyze the temporal dynamics of land use, a supervised classification (MaxVero) of the satellite imagery was established that considers weighted distances between averaged digital class levels, while the themes were identified on site. For image processing, map generation and manipulation, we used the 4:3:2 band composition of SPRING 4.3.3.

Reservoir silting scenarios: the investigation considered three reservoir silting scenarios (2010 – 2040); all of which directly depended on rainfall erosivity and the evolution of land use. In the scenarios, rainfall varied for different horizons considering, as in Krol et al (2011), the most critical values of rainfall variation (+10% of rainfall in the rainy season and -20% in the dry season). The five prevailing classes of land use and vegetation cover identified (shrub vegetation, thinned vegetation, exposed soil, agricultural use and water) were used to access the C factor.

Silting scenario (S1) - invariability: the land use conditions in the year 2010 are assumed invariant until 2040; that is, the area fractions of exposed soil (3.2%), agriculture (18.3%), shrub vegetation (25.9%), thinned vegetation (51.9%), and the area flooded by dams (0.7%) would not change throughout the simulation period. Silting scenario (S2) – degradation (high erosion): we assumed the most erodible land uses (exposed soil and agriculture) would have the largest area fractions of the imagery years (1989, 2000 and 2010; see Figure 2): 8.2% (as in 1989) and 24.9% (as in 2000), respectively. The shrub vegetation would occupy 26.4% of the area (as in 2000) and the flooded area fraction was considered to be 0.7% (as in 1989 and 2000). The hypothesis of further dam construction was not assumed in the scenarios because the number of dams in the region has achieved the hydrological saturation point. In Scenario S2, therefore, the thinned vegetation – the cover that mostly reduces erosion (SANTOS et al., 2014) – would occupy 39.8% of the catchment area. Silting scenario (S3) - preservation (low erosion).We assumed the soil conservation practices would improve and larger areas would be destined for low-erosive land uses: agriculture would reduce the C.P factor to 0.013 (instead of 0.039), occupying 18.3% of the area (as in 2010); 25.9% of the area (as in 2010) would be composed of shrub vegetation; and 51.9% of the area (as in 2010) would be covered by thinned vegetation. The flooded area would also be assumed to be 0.7% (as in 1989 and 2000), whereas the reforestation (C.P = 0.010) area would cover 1.4%, reducing the exposed soil from 3.2% to 1.8% of the total surface.

Water demand scenarios: we evaluated the following water demands associated with the Bocaina reservoir (for the years 2010 and 2040): irrigation, urban human consumption, animal consumption and ecological discharge. In the basin, irrigation has the highest consumptive use, (almost 85% for 2010) with a weighted average efficiency of 55% (ANA, 2013). Flooding is the most frequently used method and the irrigated area of the region is presently growing at a rate of 1.11% per year (IBGE, 2015). The demand scenario D1 (invariability) assumes irrigation efficiency remains at the current level (55%); while the demand scenario D2 (enhanced irrigation efficiency) assumes admits that irrigation efficiency rises to 70%, according to the plan proposed by ANA (2013). The future demands for human consumption were obtained from Piauí (2011), while animal population data were provided by IBGE (2015). Since all the rivers in the study basin are intermittent, the ecological discharges were assumed to be 10% of the reference discharge Q_{90}, defined as the reservoir water yield with an annual reliability of 90% (CAMPOS, 2010). The criterion for the calculation of the ecological discharge is the same used in the Brazilian Semi-arid Region by Vestena et al. (2012).

Water availability and water-scarcity risk: we assessed reservoir water availability using the VYELAS model (Volume-yield elasticity: ARAÚJO; GÜNTNER; BRONSTERT, 2006), which generates a curve that expresses the water yield as a function of its respective annual reliability. The model simulates the reservoir water balance using synthetic inflow series generated by Monte Carlo method, as in Campos (2010). For a given water yield, the model calculates the annual reliability. The model takes into account the reservoir operation rules implemented by basin committees (ARAÚJO; BRONSTERT, 2016). The reservoir's morphology is assumed to be represented by Equation 10 (CAMPOS, 2010). The input data of the model is presented in Table 1.

$$\mathrm{V} = \alpha . h^3 \tag{10}$$

Table 1. Input data of the VYELAS model for simulations of the Bocaina Reservoir.

Data	Source	Values
River inflow: annual average and variation coefficient (CV).	Hydrographs (period 2000-2015) from registered data by DNOCS-PI (Departamento Nacional de Obras Contra as Secas).	Annual average = 69.4 hm^3 CV = 0.40
Morphological coefficient α and reservoir storage capacity in the construction year (1985).	PIAUÍ (2016b). Height-area-volume curves.	Coefficient α = 1,667 Capacity = 115 hm^3
Morphological coefficient α and reservoir storage capacity in the bathymetric survey year (2015).	PIAUÍ (2016a). Height-area-volume curves.	Coefficient α = 2,197 Capacity = 111 hm^3
Evaporation rate of the dry season (CAMPOS, 2010)	Class-A pan from Picos Climate Station operated by Instituto Nacional de Meteorologia (INMET). For dryland reservoirs, multiply class-A pan by 0.70 - in Mamede et al.(2012) Data period:1976 – 1990	In the dry season, the average evaporation rate is 1.72 m per year

In Equation 10, V is the volume (m³), α is the non-dimensional morphological coefficient, and h is the water level of the reservoir. Due to silting, it was not possible to estimate morphological alterations for the year 2040 with the method that we used to assess the reservoir silting (Equations 1, 2, 3, 4, 5, 6, 7 , 8, 9 and 10), i.e., the method cannot assess the morphological coefficient α in the future. In order to overcome this obstacle, we used the concept of water -yield elasticity (Φ), defined by Equation 11 (ARAÚJO; GÜNTNER; BRONSTERT, 2006). Elasticity (Φ) was assessed for several reliability levels based on water yield (Qw), calculated as in Araújo; Güntner; Bronstert (2006) and on storage capacity (volume V) in 1985 and in 2015. We assumed that the average values (1985 – 2015) of the parameter Φ remained constant for the period 2015 – 2040.

$$\Phi = \frac{\Delta Qw/Qw}{\Delta V/V} \qquad (11)$$

The water-scarcity risk (ζ) of a given reservoir can be assessed as the probability of a flaw in the provision of at least one in *n* years (Equation 12, where G is the annual water supply reliability).

$$\zeta = 1 - G^n \qquad (12)$$

RESULTS AND DISCUSSION

In-situ assessment of sediment yield and reservoir silting: the annual average erosivity estimated for the Bocaina reservoir basin (1985-2015) was 3,200 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$. According to Table 2, Argisol and Quartzarenic Neosol are the soils most susceptible to erosion within the area. This however does not significantly affect the global basin erosion, since these soils occupy a small area. The Litholic Neosols and yellow Latosols, with high and medium erosion potential, occupy the largest areas. But they are located in flat areas of the highest levels of the basin, where the predominant land use and vegetation-cover causes the lowest sediment yield. The cultivation areas (with greater erosive potential among existing vegetation-cover and land use) are located mainly in the hillslopes near the banks of rivers.

The average spatial topographic factor (LS) was calculated as 2.86. All these elements resulted in the annual gross erosion of the basin (1985-2015) of up to 225 $Mg.ha^{-1}$, (Figure 3) but with a moderate annual average value (13.5$Mg.ha^{-1}$).

Table 2. Erodibility factor (K) estimated for the specific soil classes of the Bocaina reservoir basin

Soil class	Average K ($Mg \cdot h \cdot MJ^{-1} \cdot mm^{-1}$)	Area (%)
Argisol	0.052	10.5
Yellow Latosol	0.028	44.8
Litholic Neosol	0.042	39.7
Quartzarenic Neosol	0.034	5.0
Weighted average	0.036	

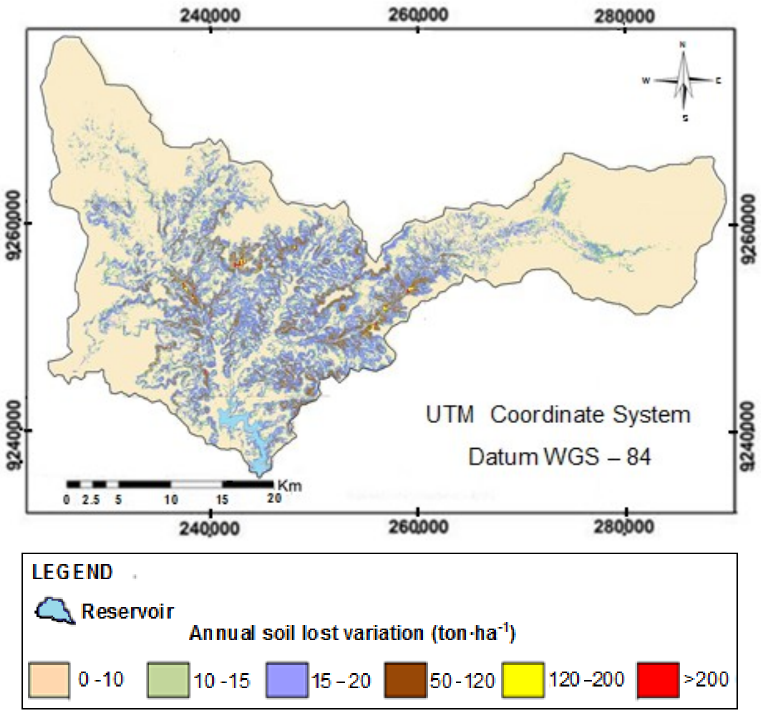

Figure 3. Annual gross erosion in the Bocaina Basin (1985-2015).

Figure 4, which compares reservoir morphology in 1985 and in 2015, shows larger accumulation values both in the delta and in the upper reaches (backwater sediment). The bathymetry (PIAUÍ, 2016a) indicated a reduction in the Bocaina storage capacity of 3.63 hm^3, or 3.2% of the initial capacity, leading to a decadal volumetric reduction of 1.0%. The silted soil dry bulk density was 1.44 $Mg \cdot m^{-3}$, whereas the trap efficiency was 0.97 (BRUNE, 1953): this led to an annual sediment aggradation rate of 0.12 hm^3in the period. Based on field data, the estimated sediment delivery ratio of the basin was 12.6%, which was considered low, generating a low annual sediment yield (1.7 $Mg \cdot ha^{-1}$). According to Medeiros et al. (2014), despite the high erosivity and moderate-to-high soil erodibility, the sediment yield in the region is usually low, leading to an equally low reservoir silting.

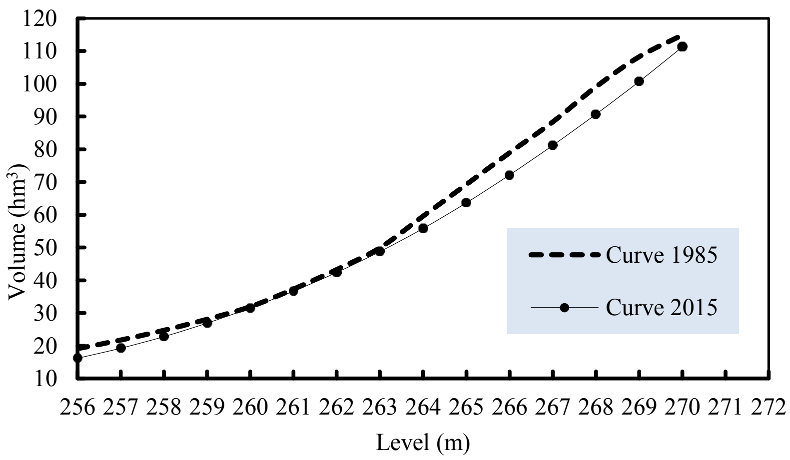

Figure 4. Curve height (level) versus volume for the Bocaina reservoir in the construction year (1985) and the control (bathymetry) year (2015).Source: Piauí (2016a), (2016b).

One of the main causes of the low sediment delivery ratio is the long dry season that limits the runoff transport capacity and induces low water and soil connectivity (MEDEIROS et al., 2014). Literature confirms the low sediment delivery ratio in the Caatinga Biome: 16% in Várzea do Boi and 12% in São Mateus (GAISER et al., 2003), 11% in Tapacurá (SILVA; SANTOS; MONTENEGRO,

2013) and 7% in Benguê (MEDEIROS et al., 2014). The Cerrado Biome, in contrast, typically shows higher values: 66% in Paraopeba (DURÃES; MELLO; BESKOW, 2016) and 28% in the Upper Iguaçu (DURÃES; COELHO FILHO; OLIVEIRA, 2016); although in some areas there are also low values of connectivity (thus, low delivery ratio), as in Água Fria (6%: SILVA; SCHULZ, 2007) and in some sub-basins of the Paraopeba River (as low as 9%: DURÃES; MELLO; BESKOW, 2016).

The measured volumetric silting rate of the Bocaina reservoir (1985 – 2015) was 1.01% per decade, almost half of the average value of the Caatinga reservoirs (1.85%) and similar to some basins, such as Acarape do Meio (1.06%) (GAISER et al., 2003). In the dry Cerrado, the silting rates are similar to those of the Caatinga, e.g., in the Três Irmãos reservoir basin (ALBERTINI; MATOS; MAUAD, 2010). In the humid areas of the biome, silting rates can be excessively high. Carvalho, Guilhon and Trindade (2000), for example, studied the Itiquira Reservoir (storage capacity of 5 hm³ and catchment area of 5,083 km²), which consists of a basin with a high erosive potential due to the prevailing land use for livestock, mining and mechanized agriculture. In addition, the reservoir presents a high catchment-area-to-storage-capacity ratio (1,017 $km^2 \cdot hm^{-3}$), which induces high vulnerability towards siltation. If constructed, the Itiquira Dam would be completely silted within eight years (CARVALHO; GUILHON; TRINDADE, 2000), at a rate 40 times higher than that observed in the Caatinga.

Regarding the low sedimentation rate of the Bocaina Reservoir, two factors stand out. Gaiser et al. (2003) showed there is a causal relation between the catchment area and the reservoir storage capacity: small ratios indicate the contribution of water and sediment to the reservoir is small. In Bocaina, the ratio is 9.1 $km^2 \cdot hm^{-3}$, almost half of the average of the Caatinga (16.7 $km^2 \cdot hm^{-3}$), which in part justifies the reduced siltation. The second factor is the preservation status of the watershed vegetation. The forested area (both shrub and thinned vegetation) occupied 77% of the territory in 1989, 71% in 2000 and 79% in 2010. This shows that the deforestation observed between 1989 and 2000 did not prevail in the subsequent period (2000 - 2010), when a vegetative recovery took place, in full agreement with the results of a remote-sensing based investigation by Redo, Aide and Clark (2012).

In terms of land use, there is the predominance of thinned vegetation (40% in 1989, 45% in 2000 and 52% in 2010), for which the land use and occupation factor (WISCHMEIER; SMITH, 1978) is the smallest (C = 0.006) among all the land uses identified in the basin. The thinning technique favors the penetration of light and consequently the formation of the herbaceous extract, which reduces water velocity and enhances sediment deposition.

Reservoir silting and its impact on water availability: based on simulations, the average annual erosivity in 2040 is expected to be 3,309 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$, 2.8% higher than the historical average for the period 1985-2015. Table 3 presents the main estimates of gross erosion and silting of the reservoir for the historical period (1985-2015), silting scenarios and the water availability of Bocaina for several reliability levels.

Table 3. Annual erosion, sediment yield, silting, storage capacity, volume-yield elasticity (Φ) and water availability (Qw, for different annual reliability levels G) in the Bocaina Reservoir for the years 1985, 2015, and 2040; considering the silting scenarios S1, S2, and S3.

	1985	2015	Φ (-)	2040		
				S1	S2	S3
Erosion ε ($Mg \cdot ha^{-1}$)	(-)	13.5	(-)	13.5	28.1	8.6
Sediment yield ($Mg \cdot ha^{-1}$)	(-)	1.7	(-)	1.7	3.5	1.1
Silting since 1985 (hm³)	(-)	3.6	(-)	7.3	11.9	6.1
Silting since 1985 (%)	(-)	3.2	(-)	6.3	10.4	5.3
Storage capacity (hm³)	115.0	111.4	(-)	107.7	103.1	108.9
Qw [G = 99%] (hm³)	41.88	41.20	0.519	40.50	39.63	40.73
Qw [G = 95%] (hm³)	48.20	46.70	0.994	45.16	43.24	45.66
Qw [G = 90%] (hm³)	52.11	50.34	1.085	48.52	46.26	49.11
Qw [G = 80%] (hm³)	57.51	55.94	0.872	54.33	52.32	54.85
Qw [G = 70%] (hm³)	62.28	60.51	0,908	58.69	56.43	59.28

By 2040 and according to the trend scenario S1, the Bocaina silting is expected to be 7.3 hm³, which corresponds to a rate of 1.1% per decade. In the least favorable scenario (S2), silting can be as high as 11.9 hm³, which represents a 1.8% volume loss per decade. The most favorable scenario (S3) estimates 6.1 hm³ silting, which implies a rate of 0.9% per decade. The 90% reliability water yield (Q_{90}) is 73% of the average annual inflow (2000-2015) (Table 1) to the reservoir (69.4 hm³), a very high ratio for the Caatinga Biome, but typical for wetter tropical environments (HUNKE et al., 2015), such as the Cerrado. Table 3 also shows that Q_{90} has decreased more intensively with time (1985-2015) than the water yield with other reliability levels (G): 3.4%; whereas for G = 70%, it decreased by 2.8%; and for G = 99%, by 1.6%. This feature is also remarkable when evaluating the volume-yield elasticity (Φ), which presents its maximum value for G = 90%.

The average Φ value is 0.88, close to that observed by Araújo; Güntner; Bronstert (2006): 0.80, for seven reservoirs in the Brazilian Semi-arid Region. The above-mentioned remarks indicate the hydrology of the focus watershed has characteristics of both biomes. Water availability (Q_{90}) in 2040 is expected to vary from 46 hm³ per year in the high-erosion scenario to 49 hm³ per year in the environmental-protection scenario. This indicates that conservationist practices can increment water availability by 6%.

Water demand and the risk of water scarcity*:* the average water demand increases for the period 2010 – 2040 (Table 4).

Table 4. Water demand from the Bocaina dam (hm³) for 2010 and 2040, for the two demand scenarios D1 and D2.

Demand	2010	2040	
		D1	D2
Human consumption	0.0	9.5	9.5
Animal consumption	0.2	0.4	0.4
Irrigation	20.9	36.2	28.5
Ecological discharge	3.7	3.7	3.7
Total	24.8	49.8	42.1

The current demands of the Bocaina system can be met with a high reliability level (above 95%) because of the still low water demand from the reservoir. At present, there is no human-supply system from the reservoir due to gaps in the sanitation policy; thus, the area is presently supplied by a network of wells. This is expected to change before 2040 because of the construction of a pipeline system designed to supply the urban areas of the dam surroundings and will increase water outtake from the reservoir at 9.5 hm³ per year. The animal-supply demand is expected to double between 2010 and 2040. The most demanding sector, irrigation, uses 84% of total current water supply.

If the irrigation efficiency remains at the same level as today (55%, scenario D1), the sector needs will increase from 20.9 hm³ per year to 36.2 hm³ per year. If, however, there is an improvement of the irrigation efficiency to 70% (scenario D2), the sector would demand 28.5 hm³ per year. In synthesis, the results show how much water availability decreases (Table 3) while demand increases (Table 4), which is particularly worrisome in water-scarce regions. Thus, a planned intervention could increase irrigation efficiency to 70% and can generate a considerable water surplus (7.7 hm³) per year, which would be enough to meet 81% of the total human demand of the Bocaina influence area. This provides an insight into the relevance of water-demand management, as opposed to the monotonic approach of water-supply management, which has characterized the regional water policy for more than a Century (ARAÚJO; BRONSTERT, 2016).

The water-availability decline of the Bocaina Reservoir was due to the silting between 1985 and 2015 and averaged 3% (Table 3). To understand the implications of this reduction, it is helpful to analyze the risk of water scarcity, as presented in Table 5, which shows the superposition of both effects and the decadal risk of water scarcity in each composed scenario.

Table 5. Analysis of combined silting (S1, S2, and S3) and demand (D1 and D2) scenarios for the year 2040 in the Bocaina Reservoir: annual reliability of the water demand and risk of decadal water scarcity.

Scenarios	S1 (invariability)	S2 (degradation)	S3 (preservation)
	Annual demand reliability in 2040		
D1 (invariability)	0.88	0.84	0.89
D2 (enhanced irrigation efficiency)	0.98	0.96	0.98
	Risk of decadal water scarcity in 2040		
D1 (invariability)	0.72	0.82	0.68
D2 (enhanced irrigation efficiency)	0.20	0.32	0.17

The trend scenario (S1-D1) indicates an excessively high risk of decadal water scarcity (72%), which means that an intervention is advisable so as to avoid a water collapse in the area. For demand scenario D1, water reliability would be inferior to the desirable level (90%), whatever the silting scenario, which is a strong indicator that this scenario will lead to a non-sustainable situation, considering that a 90% annual reliability is the planning parameter for the Brazilian dry region (CAMPOS, 2010). Contrastingly, an improvement of irrigation efficiency would generate high reliability (above 95%) of water supply by 2040.

The worst combined scenario (S2-D1) shows an extremely high decadal risk of water shortage (82%) in 2040, caused by the combination of environmental degradation (S2) and the lack of a water-demand policy (D1). In contrast, the combination of an environmental conservation policy (S3) and an improved irrigation technology (D2) has the potential to reduce this risk to 17%. The beneficial potential of changing the land use can be noticed by comparing the scarcity risk of the combined scenarios S2-D1 with that of S3-D1, which would considerably lower the risk from 82% to 68%. Nonetheless, the benefit caused by changes in irrigation efficiency is even higher: the scarcity risk can be reduced from 82% (S2-D1) to 32% (S2-D2), which shows the relevance of a water-demand management for the hydric policy of the Brazilian dry region.

CONCLUSION

Field measurements (1985 – 2015) indicated gross erosion in the watershed Bocaina reservoir of 13.5 $Mg \cdot ha^{-1} \cdot yr^{-1}$, sediment delivery ratio of 12.6% and annual sediment yield of 1.7 $Mg.ha^{-1}$. Despite the high gross erosion, sediment yield was low mainly due to hydrological constraints, which limit sediment-transport capacity and reservoir silting (1.0% per decade). The average volume-yield elasticity was 0.88, i.e., the decadal water-availability reduction was 0.88%.

Considering the increase in water demand until 2040 in the scenario without improving the efficiency of irrigation methods applied in the basin, supply reliability is expected to be unsatisfactory (below 90%), regardless of the silting scenario. Nonetheless, if irrigation efficiency rises from 55% to 70%, supply reliability surpasses 95% for any silting scenario. The integration of both strategies (soil preservation and increased irrigation efficiency) can reduce the decadal water-scarcity risk from 82% (worst scenario) to 17%. Between both strategies, demand management has proven to be more effective.

The results of this research are a relevant guide for decision makers in planning the supply of water-demands in the Bocaina Reservoir, considering the existing water conflicts and as support for the management of water resources in such a water-scarce region. Among the relevant issues that were not tackled in this investigation, we mention (a) the impact of surface-reservoir siltation on water quality and hence, on water availability; and (b) the contribution of a water-reuse policy (integrated with environmental preservation and demand management policies) to the societal adaptation to water-scarcity situations.

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