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Water Management causes increment of reservoir silting and reduction of water yield in the semiarid State of Ceará, Brazil

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ABSTRACT

The semiarid State of Ceará, Brazil, implemented its water management system in the early 1990s. The drought-prone State is densely populated and its supply strongly relies on surface reservoirs, whose yield reduces with silting. Using artificial neural networks and data from 141 monitored dams, we show that the silting ratio of the reservoirs significantly enhanced after the implementation of the water management system. An explanation for this fact is that, since the management started, water withdrawal increased, leading to lower reservoir levels at the beginning of the rainy season. This reduces the probability of spilling, which is the main mechanism of sediment outflow, thus causing excessive siltation. As a result, water availability is expected to reduce by 6% in 30 years, creating a clear contradiction with the management objectives. To tackle this problem, four actions are recommended: to include spilling in the operational rules, to reduce erosion in the basins, to execute sediment reuse policy, and to implement water-demand management.

1. Introduction

The scarcity of water is one of the main problems of dryland societies (Sharafatmandrad and Mashizi, 2020). The Brazilian state of Ceará, located in the Caatinga Biome, semiarid region of the Country, has suffered the consequences of water scarcity for many centuries (Gaiser et al., 2003), mostly due to the intermittence of its rivers associated with long lasting droughts and high demand (Aragão Araújo, 1990). As a result, in the end of the XIX Century, the federal government started the so-called *hydraulic policy*, which consisted of building dams and the associated infrastructure to store the water surplus of the wet months to dispose of it in the dry season (Medeiros and Sivapalan, 2020). The first striking action of this policy was the construction of the Cedro Dam (126 hm^3) between 1878 and 1906. The monotonic approach of dam building prevailed until the late 1980s, when a new water policy was established (Campos, 2015). The State installed a novel institutional framework to tackle the water issue in 1987; in 1991 the first water resources plan was published; in 1992 the new State water law was enacted; in 1993 the Water Resources Company (COGERH, which acts as the water agency) was created; and in 1994 the first river basin committee was installed. Because of their relevance to the water supply in Ceará (Aragão Araújo, 1990; Krol et al., 2011; Alves et al., 2012; Peter et al., 2014; Campos, 2015), surface reservoirs remain central to the management approach.

In Brazil, the water-management era boosted in the early 1990's, shortly after the implementation of the Country 1988 democratic constitution (Keck and Abers, 2004; Campos, 2015). The national policy was formally established when the new federal water legislation was enacted in 1997, five years after the approval of the Ceará State law. The new legislation improved considerably in comparison with the former (from 1934), whose main focus was the generation of hydro-power. Among the legal advances, there are the assertions that the water is a public good; that it must benefit multiple uses; that water quality must be ensured; and that the decision-making process must be participatory by means of democratically-elected river basin committees. Despite the merits of the new system, several concerns have been raised, such as the prevailing influence of powerful corporations to the detriment of less influential societal sectors (Broad et al., 2007; Moraes and Perkins, 2007; Taddei, 2011; Libanio, 2018; Salinas et al., 2019; Miranda and Reynard, 2020).

The question raised hereafter is whether the implementation of the water management could have notably changed the water balance and, thus, the sediment redistribution pattern in the basins. In fact, de

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Araujo et al. (2006) showed how surface-reservoir siltation causes depletion of the water yield with time, which is a serious drawback for semiarid regions. Our key concern is that eventual changes caused by the new management practices may reduce the water availability with time, generating a serious contradiction. The objective of this work was, then, to verify, based on data from 141 monitored dams in Ceará, if the siltation pattern changed after the implementation of the water-management system (1992/1993) and, if confirmed, to which extent these changes would bounce back to the water availability.

2. Methodology

2.1. Study area

The study area is the Brazilian semiarid State of Ceará, whose geological history took place with greater propriety from the Cretaceous, with the rupture of the South American and African continents. This resulted in the uplift of past features (Sertaneja Depression, Ibiapaba mountain and the residual massifs), giving rise to the Cariri-Potiguar structural axis. The formation of the respective basins and the main plateaus (Araripe and Apodi) gave rise to the current configuration of the State coastline. Throughout the Neogene and Quaternary, the territory of Ceará underwent several climatic and eustatic variations, with the deposition of sediments from the Barreiras Formation and its respective relief called coastal tablelands, in addition to the macro-configuration of the drainage network. The State has two major geological domains: sedimentary and crystalline lithologies, encompassing magmatic and metamorphic rocks. Three major soil classes were modeled on these domains: Neosols, Argisols, and Luvissols (De Matos, 2000; Bezerra et al., 2001; Cavalcante et al., 2003). In meso-scale basins (10^2–10^3 km^2), the relief is moderate, with average slope of 13%, typically ranging from 5% to 20%. In the hinterlands, where water is scarce and soil is shallow, the main land use is non-intensive agriculture (typically corn, beans, cassava, and rice) associated with cattle and goat breeding; whereas in the coastal, alluvial and mountainous regions, intensive fruit crops are often cultivated (Gaiser et al., 2003).

With a surface of 148,000 km^2 and 9.1 million inhabitants, Ceará has a critical water deficit to the atmosphere: the average precipitation is below 800 mm yr^{-1}, whereas its potential evaporation surpasses 2000 mm yr^{-1}. Besides, more than 85% of its territory is located on top of the crystalline basement, where rivers are intermittent and groundwater is scarce and frequently salty (Gaiser et al., 2003; de Figueiredo et al., 2016). Additionally, the Brazilian semiarid region is often affected by droughts (Marengo et al., 2017; Medeiros and Sivapalan, 2020) that may last several years (de Araújo and Bronstert, 2016; Marengo et al., 2018). Due to the dry spells and to the high demand, water disputes have frequently disrupted conflicts (Aragão Araújo, 1990; Taddei, 2011). In order to solve this problem, decision makers built a dense, complex network of on-river reservoirs that supplies approximately 90% of the State water demand (Mamede et al., 2012). According to Peter et al. (2014), there are tens of thousands of dams in the State of Ceará, built continuously during one hundred years (mostly from 1910 to 2010), whose sizes range from micro (10^{-2} hm^3) to very large (10^4 hm^3). This complex network reduces the system vulnerability towards hydrological extremes, both droughts and floods (Peter et al., 2014). It also impacts the system water availability (Krol et al., 2011; Malveira et al., 2012), energy balance (Nascimento et al., 2019), and sediment redistribution pattern (Lima Neto et al., 2011; de Araújo et al., 2017).

What concerns sediment dynamics in Ceará, de Araújo et al. (2017) gathered measurements from 26 sites of the Jaguaribe River Basin (75,000 km^2), the largest in the State. The sites, which have different catchment areas (10^{-4} –10^{+4} km^2) and various monitoring techniques, show that sediment yield in the basin ranges from 10^0 to 10^3 Mg km^{-2} yr^{-1}. The authors identify the catchment area, the presence of numerous small dams upstream, and the basin geology as the key factors influencing sediment yield in the Jaguaribe Basin. Lima Neto et al. (2011), who assessed SY in the Upper Jaguaribe Basin (24,600 km^2) based on data from 25 years, concluded that the retention caused by the dense network of small and middle-sized reservoirs is considerable, trapping almost 60% of the whole basin sediment yield. Farias et al. (2019) showed that unpaved rural roads, which contribute to 16% of SY in the Upper Jaguaribe Basin, are a factor that should be regarded when managing sediment in Ceará, considering its long rural-road network. Besides, Oliveira et al. (2016) have found evidences of organochlorine pesticides in the sediments of the Jaguaribe River, which also threatens its water availability.

2.2. Reservoirs morphological data

We selected 141 monitored dams in Ceará (Fig. 1 and Table 1), among which the one hundred largest ones in the State. All selected reservoirs dispose of morphological data both in the construction and in a control year. The control surveys consisted on the reservoir bathymetry, undertaken after the implementation of the new State water policy by the management company (COGERH), except for the Marengo (Zhang et al., 2016) and the Aiuaba (de Figueiredo et al., 2016) dams, which are monitored by the HIDROSED Research Group. The bathymetric surveys used the accurate methodology explained in detail by Lopes and de Araújo (2019). It is relevant to stress that, although the selected cluster represents only 0.5% of the existing dams in the State (Mamede et al., 2012), its storage capacity encompasses almost 15 km^3 (85% of the State capacity), whereas its yield with 90% annual reliability Q_{90} adds to 4.5 km^3 yr^{-1}, or 89% of the State surface-water availability.

2.3. ANN test of hypothesis

The hypothesis that water management changed reservoir siltation (see Table 1) was tested using Artificial Neural Networks (ANNs, see also Meshram et al. (2020)) to derive the siltation pattern for the reservoirs of Ceará. We assume that the collected data forms a representation of continued reservoir management in Ceará, i.e., a generalized time series. Key water governance events, like the new State Water Law in 1992 or the establishment of the Water Resources Company in 1993 and their subsequent management decisions, are assumed to impact the time series of water and sediment budgets. As the nature and effect of governance decisions are non-linear, its impact – and thus our hypothesis – on the time series data is non-linear, as well. ANNs are supreme tools to detect such kind of comportment within complex data (Schmidhuber, 2014; Michelucci, 2018).

Four ANNs (Long Short-Term Memory (LSTM), Feedforward Neural Network (FFNN), Multilayer Perceptron (MLP), Support Vector Machines for Regression (SVR)) were utilized based on tensorflow, scikit-learn and keras libraries to learn from the collected data (with focus on inauguration year and siltation per decade) in two 60-fold data augmentation configurations (jitter (pure Gaussian noise) and warp (Gaussian noise on Bezier-Curves) Um et al., 2017; Le Guennec et al., 2016; Xiao and Xu, 2012) to guarantee that results were independent of the ANN methodology.

Other techniques were utilized to optimize the respective ANNs performance, among them synthetic minority oversampling technique (SMOTE) (Fernández et al., 2018) and an iterative k-fold cross-validation grid search process, based on median absolute deviation (MAD) (Gorard, 2013) for optimized ANN hyperparameters (Jiang and Chen, 2016). The chosen hyperparameters for each network are displayed in Fig. 2.

The networks are trained via k-fold cross validation, i.e., they are trained on k-1 parts of the augmented data set and blind-tested on the remaining k-part. In the training phase, the network interactively tries to generate emulations that explain the decadal sedimentation comportment of the received data, by reducing the error between

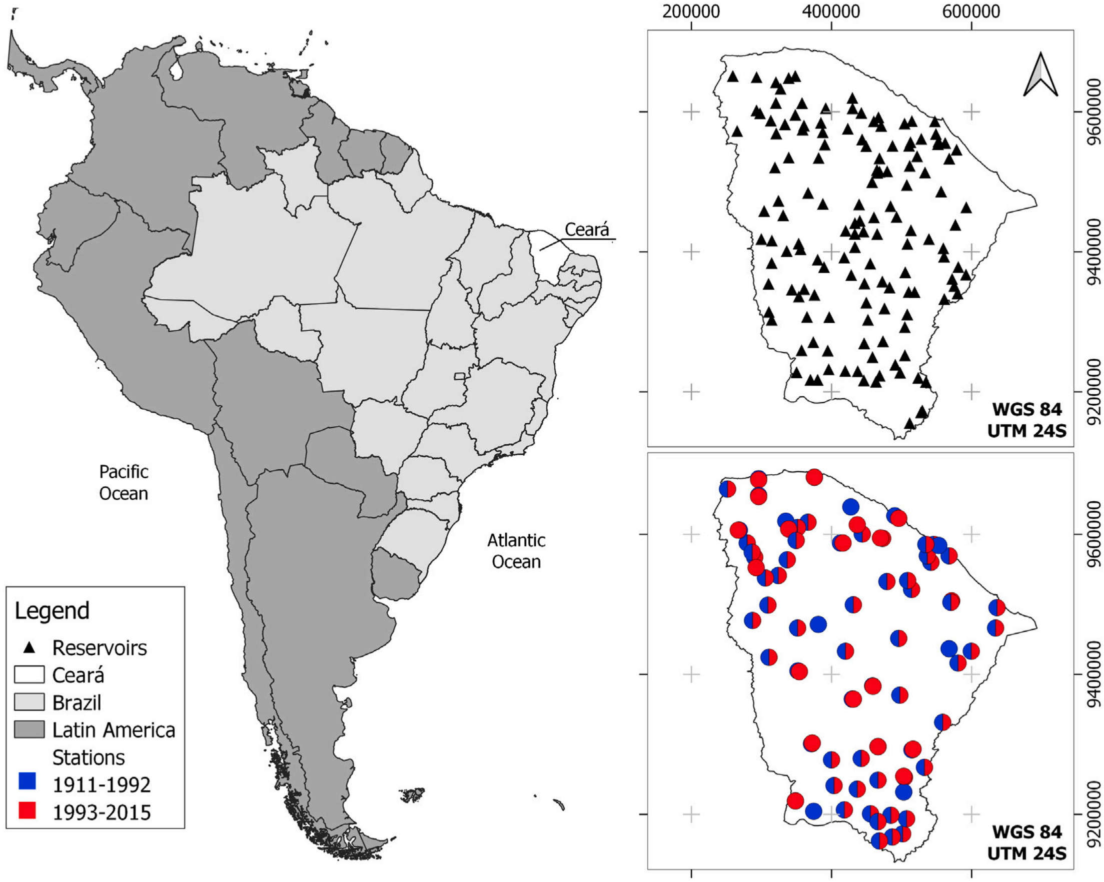

Fig. 1. Location of study area, 141 reservoirs and 73 rainfall gauging stations. In color we indicate the time periods of usage of each station.

Hyperparemter	SVR	FFNN	LSTM	MLP
Learning Rate	-	0.01	0.008	0.003
Batch Size	-	128	200	32
Optimizer	-	Adam	Nadam	Adam
Loss Function	-	logcosh	logcosh	-
Activtion	-	ReLU	ReLU	tanh
Epochs	-	5	12	automatic
Dropout	-	0.1	0.1	-
Hidden laye setup	-	700/150/25/50/1	1000/200/16/1	100/50/1
k-fold emulation	-	6	4	4
C	60	-	-	-
Gamma	3	-	-	-
Epsilon	0.004	-	-	-
Kernel	rbf	-	-	-

Fig. 2. K-fold cross-validated grid searched hyperparameters of the respective networks.

the own emulation and the known training data result via the loss function (Schmidhuber, 2014; Michelucci, 2018). The final test on unknown test data demonstrates the network's capability to generalize on data and not to merely copy (i.e., overfit) known behavior from the training data.

The uncertainty associated with ANN in the present study derives mainly from the limited data, field-measurement errors, and ANN topology. The reduced data availability occurs because, in Ceará, there are only 141 reservoirs with control-bathymetry data. This is partly justified because reservoirs managers started assessing siltation patterns not earlier than the new water-management system implementation, in 1993. Besides, in a region where average decadal siltation rates are less than 3%, bathymetric surveys only yield meaningful siltation data for time steps of at least a decade. Additionally, there is the field-measurement associated uncertainty, which depends on assessment errors in the original topography and in the control bathymetry. According to Kasiviswanathan and Sudheer (2017), besides model-associated inaccuracy, ANN network topology is also a source of uncertainty, although not always accounted for

2.4. Oversiltation impact on water yield

To assess the impact of oversiltation on water yield, we simulate two scenarios. Scenario 1 assumes the siltation rate as observed before the implementation of the management practices in 1993; whereas scenario 2 considers the siltation rate as observed after the practices. Starting in the bathymetry year for each individual reservoir, the temporal horizon of both scenarios is 30 years, which is justified mainly by two reasons. First, in contrast with degraded areas (Simplício et al., 2020; de Jesus et al., 2022), the measurement of reservoir siltation in moderate-erosive regions, such as Ceará, not always provides reliable results for periods smaller than ten years (Gaiser et al., 2003). Secondly, the focus of the research is the water resources planning, which often considers a three-decade horizon (Campos, 2015). The VYELAS model (de Araujo et al., 2006), which is used to compute the water yield, simulates the water balance in the reservoirs using a Monte Carlos synthetically-generated inflow series and mimics operation rules commonly practiced in the State of Ceará (see, e.g., de Araújo and Bronstert (2016)). The model demands data of seasonal water inflow (average and standard deviation), precipitation, evaporation, storage capacity (SC), alert volume, and the morphological parameter α (Eq. (1), where y_{max} is the water maximum depth: Campos (2010)).

$$SC = \alpha . y_{max}^3 \quad (1)$$

Eq. (2) represents the temporal evolution of the storage capacity as a function of the siltation rate (r, see Table 1), which was estimated based on data from the inauguration and bathymetry years for each individual reservoir. The index 0 refers to the initial year of analysis. Eq. (3) also depicts how SC varies with time (t), but as a function of the rainfall erosivity (R, given in MJ ha^{-1} mm h^{-1} yr^{-1}) and of the siltation parameter (ξ). Due to the scarcity of sub-daily rainfall measurements in the XX Century in Ceará, we use Eq. (4) (Lombardi Neto and Moldenhauer (1992), validated by de Araujo et al. (2006) in the State), in which H(t) is the total monthly rainfall (mm) and $\bar{H}$ is the average annual rainfall (mm). A total of ninety rainfall stations (Fig. 1) with consistent monitoring were selected to assess the erosivity in Ceará (FUNCEME, 2020). All stations monitor daily precipitation using *Ville de Paris* gauges and were tested for consistency and missing values. From the set of selected stations, two subset were formed: the first has sixty-nine stations with more than thirty complete years (with no missing data in the rainy season) from 1911 to 1992. The second subset has seventy-three stations with more than fifteen complete years to assess erosivity from 1993 to 2016. For each reservoir, the rainfall erosivity is taken from the closest rain gauge.

$$SC(t) = SC_0.(1-r)^{\Delta t} \tag{2}$$

$$SC(t) = SC_0.\left[1 - \xi.\sum_{t=1}^{\Delta t} R(t)\right]^{-1} \tag{3}$$

$$R(t) = 68.73.\sum_{i=1}^{12}\left[H(i,t)^2/\bar{H}\right]^{0.841} \tag{4}$$

In order to estimate the value of the siltation parameter in the recent period (ξ_{rec}), i.e., after the management practices implementation, we apply Eq. (3) to the 40 reservoirs that have been constructed since 1993. This yields average $\xi_{rec} = 1.13\ 10^{-6}$ MJ^{-1} ha mm^{-1} h yr. Then, for each reservoir built before 1993, Eq. (5) is applied to estimate its respective parameter ξ_{old}. The average siltation parameter of the pre-1993 period ($\bar{\xi}_{old}$) equals 7.88 10^{-7} MJ^{-1} ha mm^{-1} h yr. The changes in the reservoir morphology can be estimated using Eq. (6), whose parameter (K_α) is computed using the morphology in both construction and bathymetry years (see Table 1).

$$\Delta SC/SC(t) = -\left[\bar{\xi}_{rec}.\sum R(\Delta t)_{rec}\right] - \left[\xi_{old}.\sum R(\Delta t)_{old}\right] \tag{5}$$

$$Ln\left[\frac{\alpha(t)}{\alpha_0}\right] = -K_\alpha.\frac{\Delta SC(t)}{SC_0} \tag{6}$$

The key dynamical quantities to assess the impact of siltation on water yield using the VYELAS model are the reservoir storage capacity and its respective morphological parameter α. In the analysis, we assume stationary climate. Eq. (3) is used to assess the storage capacity 30 years after the bathymetric survey. For scenario 1, we assume ξ equal to the average ξ_{old}, whereas for scenario 2, ξ equals the average ξ_{rec}. The changes in morphology (α) are computed using Eq. (6) with parameter K_α derived from the period between inauguration and bathymetry years for each reservoir. We assume that the difference of parameter K_α within three decades for both scenarios is negligible.

3. Results

3.1. ANN test of hypothesis

The results of the ANN emulations in Fig. 3 (the boldness of the graphs reflect the degree of uncertainty of the networks) are mostly concordant for both data augmentation types, with some inconsistencies for the MLP warp, probably caused by higher outlier sensitivity (Khamis et al., 2005). LSTMs demonstrate a way lower change for post-1990 data, presumably as they are more robust to short-run deviations compared to the other ANNs (Shah et al., 2018).

Siltation per decade is stable at low positive rate for all network types for most of the decades, as Fig. 3 demonstrates. With the onset of the water management change in the beginning of the 1990s, the sedimentation rate experiences a steep rise for most of the networks (excluding LSTMs). The decadal siltation reaches 20% for the reservoirs managed completely under the new directive. The networks derived that there exists a substantial difference in decadal siltation for the pre- and the post-1993 condition. The network metrics correspond with and are based on the same character as the ones described by Landwehr et al. (2020). This confirms the hypothesis that the siltation patterns differ before and after the implementation of the management system.

3.2. Oversiltation impact on water yield

Table 1 presents the main results concerning the historical siltation between inauguration and bathymetry years. On average, the 141 reservoirs silted 10% (total SC reduced from 19.5 to 17.5 km^3) in the mean period of 40 years (1973–2013). The decadal siltation rate (r) averages 2.7%, but the individual values vary considerably (from 0.2% to 56.6% every ten years), so that the coefficient of variation surpasses 1.3. There are five reservoirs (3.5% of the studied sample) whose decadal silting rates surpass 20%. This is mainly caused by two processes, namely, high bulk erosion in the upper basin and high catchment area per unit storage capacity (A:SC) ratio. The upper basin of the reservoir with highest silting ratio (56.6% per decade) is located in the Maranguape Mountain, where precipitation is high (1150 mm annually); where the steep slopes are prone to extremely erosive events (e.g., 204 mm on 24 February 2009: FUNCEME); and where environmental preservation status is low to moderate. The other four critical reservoirs have very high A:SC ratios (average of 75 km^2/hm^3), whereas the State average approaches 10 km^2/hm^3. In the other extreme, the reservoirs with very low silting rates (e.g., 0.2% per decade) have high density of upstream dams, which have proven to be extremely efficient in trapping sediment (Lima Neto et al., 2011).

Table 1 also shows the temporal changes of the morphological flatness of the reservoirs (α). The mean historical values of the parameter α increase from 9211 to 10,710, i.e., 16% increment over four decades, on average. In general, the α values increased from 2% to 30%, however, in some cases, the flatness almost doubled, as in the Varzea Volta Reservoir. Likewise, the parameter K_α (average of 1.890) varies largely, from 0.003 to 4.914, with coefficient of variation of 0.75. In general, the morphological flatness of the reservoirs is increasingly related with the storage capacity. The parameter (α) of the 10% (14) largest reservoirs averaged almost 21,000 in the construction year, but over 23,000 in the bathymetry year; whereas for the 10% (14) smallest dams, the α values are 1160 and 1573, respectively. Despite this trend, outliers are frequent due to local relief conditions. For example, relatively small dams may have α values similar to the largest ones, as are the cases of Lima Campos (the 33rd largest) and Varzea Volta (only the 93rd largest) reservoirs.

From Fig. 4 one can depict that the annual erosivity in Ceará is high (up to 12,000 MJ ha^{-1} mm h^{-1} yr^{-1}) with significant spatial variation: the maximum R values are more than twice the lowest ones. Erosivity is maximum in the relatively wet northwestern and coastal regions, surpassing 10,000 MJ ha^{-1} mm h^{-1} yr^{-1}. The low-erosivity region is mainly located in the very dry central and southwestern region of the State, where R is usually lower than 6000 MJ ha^{-1} mm h^{-1} yr^{-1}. The sub-humid southeastern region represents well the average erosivity of the State. The comparison of erosivity in both analysis periods (1911–1992 and 1993–2015) shows that the average values did not change, except for the area in the central western region, where R reduced from 10,000–12,000 to 7000–8000 MJ ha^{-1} mm h^{-1} yr^{-1}. For the whole analysis period, the State erosivity averages 6278 MJ ha^{-1} mm h^{-1} yr^{-1}.

The results of the scenarios analysis can be depicted from Table 2 and Fig. 5. The storage capacity of the 141 reservoirs, which totaled

Table 1
Data from the 141 investigated reservoirs in Ceará both in construction and in bathymetry years (measured storage capacity (SC) and morphological parameter (α)), as well as decadal silting rate (r) and the morpho-dynamical parameter (K_α). The upper part of the table shows specific results for ten selected reservoirs of different storage-capacity orders of magnitude. Each reservoir ranking refers to its respective storage capacity. The lower part of the table shows the main statistical parameters.

Ranking	Reservoir	Construction			Bathymetry				K_α
		Year	SC (hm^3)	α (−)	Year	SC (hm^3)	α (−)	Decadal silting rate	
1	Castanhao	2002	6700	34,339	2012	5738	36,442	0.144	0.355
4	Araras	1958	980	21,005	2014	860	22,659	0.023	0.541
8	Pentecoste	1957	396	32,517	2009	360	41,483	0.018	2.461
17	Aracoiaba	2003	162	6310	2015	154	6743	0.043	1.220
33	Lima Campos	1924	66	24,192	2016	62	31,746	0.007	3.848
41	Varzea Boi	1954	52	15,381	2010	47	17,258	0.016	1.198
52	Malcozinhado	2003	37	10,830	2015	33	12,778	0.072	1.776
93	Varzea Volta	1919	13	12,500	2000	11	23,180	0.016	4.529
111	Bonito	1964	6.0	6000	2013	5.6	7736	0.015	3.407
141	Aiuaba	1934	0.062	561	2009	0.059	652	0.006	3.535
Average (n = 141)		1973	138	9211	2013	124	10,710	0.027	1.890
St dev (n = 141)		29	611	10,787	3	530	12,144	0.036	1.423
CV (n = 141)		0.015	4.43	1.17	0.001	4.29	1.13	1.33	0.75
Minimum (n = 141)		1900	0.062	134	2000	0.059	145	0.002	0.003
Maximum (n = 141)		2013	6700	65,070	2019	5738	66,505	0.566	4.914

17.5 km^3 in the bathymetry years, is expected to reduce to 14.9 km^3 according to scenario 1, and to 13.8 km^3, should scenario 2 occur. This represents a considerable loss of volume in only three decades: 15% and 21% for scenarios 1 and 2, respectively. The enhanced siltation pattern of scenario 2 is also expected to deliver more open morphology (higher α values) in the reservoirs than in scenario 1: on average, 17,666 and 15,002, respectively. The direct result of this pattern is the occurrence of higher evaporation discharges from the lakes with time. The trend of higher α values in the largest reservoirs also prevails in the scenarios. However, the difference of flatness among large and small reservoirs tend to attenuate with siltation intensity: the ratio between α in the 10% largest and in the 10% smallest reservoirs reduce from 15.02 to 14.88 for scenarios 1 and 2, respectively.

Based on the results of Table 2, we observe that, for scenario 2, i.e., after the implementation of the water management system, the capacity of delivering water with high reliability (Q_{90}) decreases. The average water availability reduction due to oversiltation in 30 years is 6%: from 31.8 to 29.9 $hm^3\ yr^{-1}$ per reservoir. Fig. 5 displays the water availability reduction in scenario 2, when compared with scenario 1, which is expected to occur for all monitored reservoirs, without exception. In extreme cases, siltation can cause the reduction of more than 50% of the water yield within three decades. From Fig. 5 one can observe that the impact of oversiltation on water yield (i.e., the difference between Q_{90} for both scenarios) affects more severely the smaller reservoirs, which may bring further difficulties for the sparse rural population: the difference is notably larger for the 14 smallest than for the 14 largest dams, for example. Fig. 5 and Table 2 also show a relevant hydrological feature in the Brazilian drylands, where water availability (Q_{90}) averages only 20% and rarely reaches half of the inflow discharge (Q_{in}), whatever the scenario. It is also notable that smaller reservoirs have lower hydrological efficiency (Q_{90}/Qin), mainly due to their small depths associated with high local evaporation rates. However, there are exceptions, such as the Lima Campos reservoir (Table 2), one of the 25% largest reservoirs, whose hydrological efficiency is as low as that of the smallest ones. In fact, in scenario 1, the 10% (14) largest reservoirs yield 39% of the inflow discharge, whereas the 10% (14) smallest ones only yield 12%. In scenario 2, the efficiency rates reduce even further: 37% and 10% for the largest and smallest dams, respectively.

4. Discussion

Due to the intermittence of the rivers and to the quali-quantitative limitation of groundwater, on-river reservoirs generated by dams have been the most relevant form of supplying water in the semiarid Brazilian region, where the State of Ceará is located. As a reservoir reduces its storage capacity due to the sediment trapping, its morphology tends to become flatter, which implies larger evaporation discharges. Besides, siltation also reduces its capacity to store water in the rainy season. Therefore, if the hydrological and water use conditions do not change, siltation may cause an increase of spilling. The long-term water balance of reservoirs shows that the inflow discharge has four main destinations: withdrawal, evaporation, spilling (Campos, 2010) and, less important, infiltration (Mamede et al., 2012). The increment of evaporation and spilling, thus, tends to cause reduction of water yield, as proven elsewhere (de Araujo et al., 2006). Some argue that the dense network of small dams in the Brazilian semiarid region harms the sustainability of the water system. However, several researchers prove otherwise (Mamede et al., 2012; Malveira et al., 2012; Peter et al., 2014; Nascimento et al., 2019). Lima Neto et al. (2011) argue that, among the benefits of the small dams, there is the fact that they trap almost 60% of the sediment yield, reducing the siltation of the middle-sized and large reservoirs and, thus, benefiting the whole system in the long run.

Data from Table 1 show that, on average, the reservoir network storage capacity decays by 2.7% per decade in the State. de Araujo et al. (2006) measured siltation in seven reservoirs in the same State and concluded that, on average, the decadal siltation rate was almost 2%, thus, lower than the results from this research. The reason for the difference of the siltation rates may derive from the representativeness of the data set (the previous work sampled only seven reservoirs against 141 here), but it may also be related with the time of the bathymetric surveys: de Araujo et al. (2006) surveyed the reservoirs few years after the establishment of the water management system, whereas in the present research the time lag was, on average, two decades. The ANN results (Fig. 3) for eight different configurations confirm the assumption that the siltation after 1993 is significantly higher than before the implementation of the water management system. It is important, however, to note that the increase on the siltation rate as a result of intensive water use is a transient process, which may have different outcomes, depending on how reservoirs are managed. First, managers must decide on whether the reservoirs will be submitted to periodic dredging or not. In affirmative case, the reservoirs morphology recovers, and the process re-starts. However, if dredging is not adequately performed (in terms of amount and/or frequency), the system evolution depends on a second decision, i.e., whether water withdrawal will be adjusted to the changing reservoir storage capacity or not. If withdrawal remains constant, spilling increases with time due to siltation, which causes in turn lower sediment trapping (Pereira et al., 2022). This new hydrological pattern leads to a novel system equilibrium state, with siltation rate lower than that measured in the present study and moderate decrease water availability. However, if

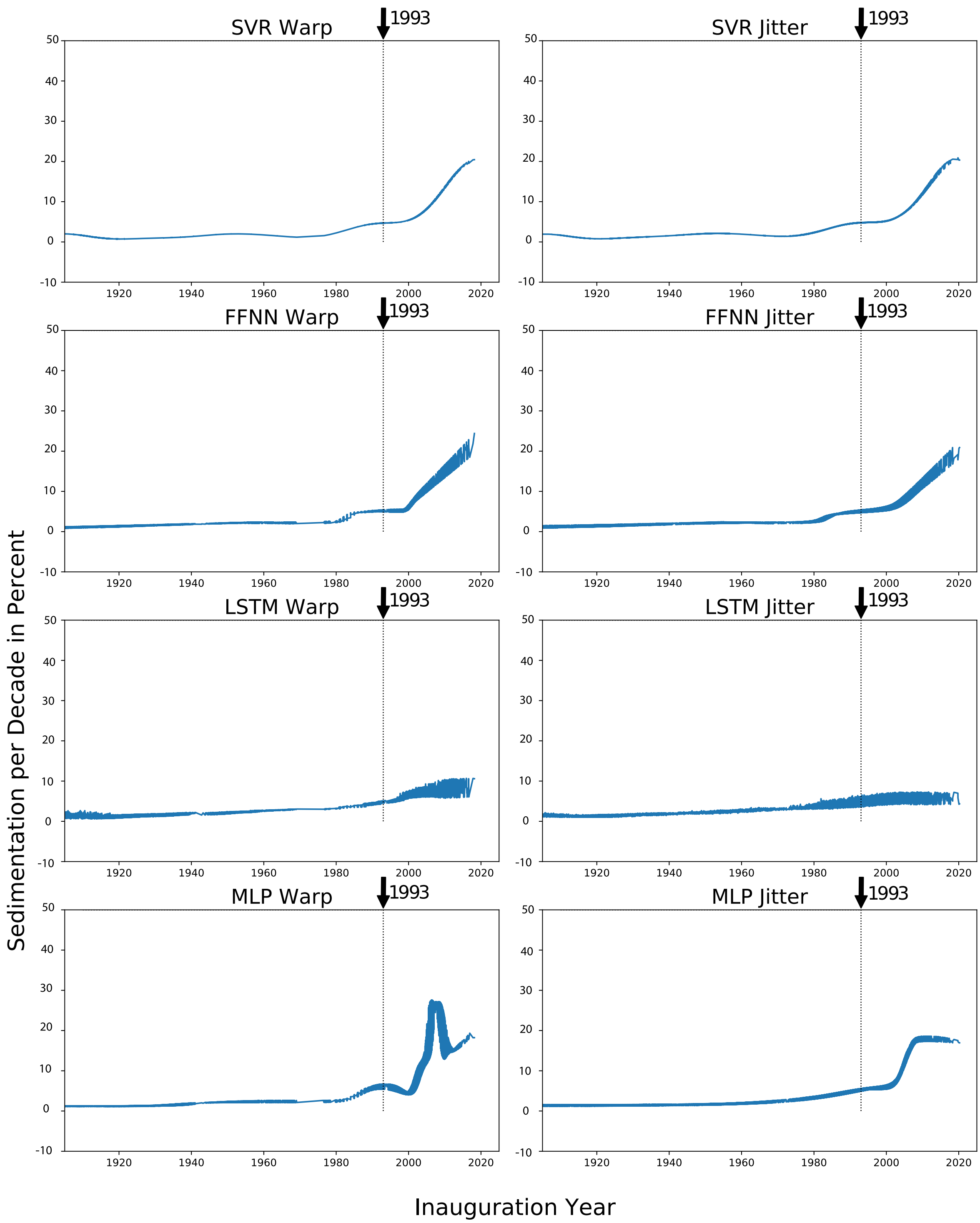

Fig. 3. Results of artificial neural networks concerning the decadal siltation rate in the State of Ceará.

water withdrawal follows the zero-spilling paradigm, high siltation rates continue to occur and water availability is expected to lessen more rapidly.

Scenario 1, despite the assumption of lower siltation rate, shows that storage capacity in the State can reduce by 15% within three decades (Table 2), which is of serious concern, especially considering that surface reservoirs (as the 141 ones investigated here) respond to 90% of the State water demand. In scenario 2, the situation is even more drastic, with expected reduction of 21% of the storage capacity in 30 years. In the scenario analysis (Fig. 5), it is clear that the water availability reduction is more pronounced in the small reservoirs, which are the ones that already dry out more often (Brasil and Medeiros, 2020; Medeiros and Sivapalan, 2020). Additionally, reservoir morphological flatness parameter α increases with the siltation rate. Reservoirs with higher α are more prone to evaporate, which is also a relevant factor influencing the decrease of water availability. This means that, for scenario 2 (i.e., higher siltation rate) more open morphology is expected with time, leading to higher evaporation and, thus, to lower water

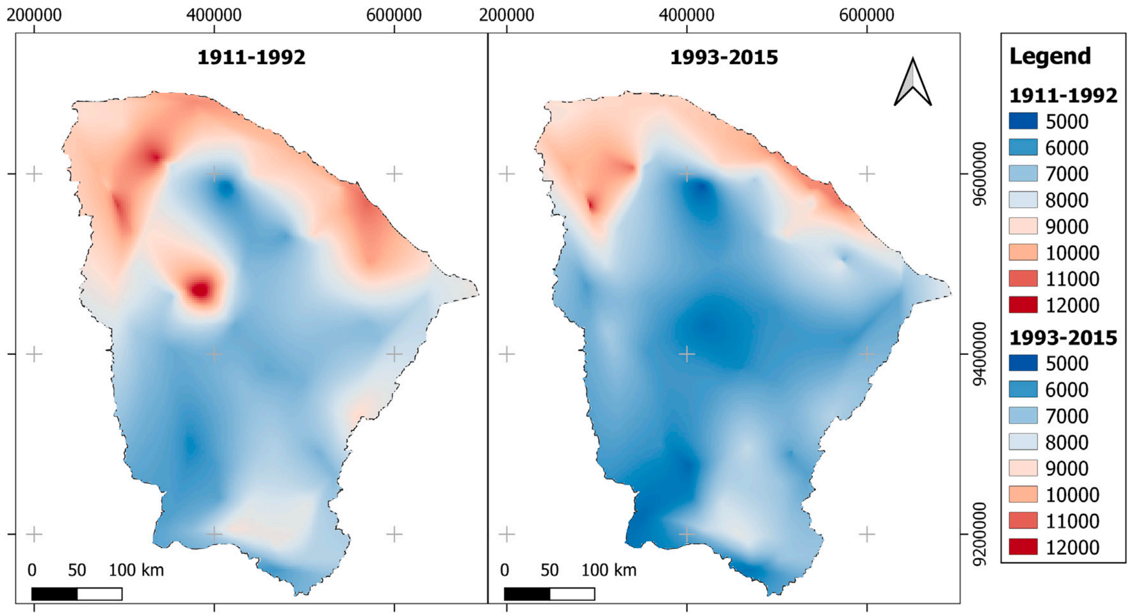

Fig. 4. Average yearly erosivity over the State of Ceará from the periods of 1911–1992 (left) and 1993–2015 (right).

Table 2
Simulated storage capacity (SC), morphological parameter (α), water yield (Q_{90}), and its ratio to the average inflow (Q_{in}) for two 30-year horizon scenarios. The last column shows the Q_{90} relative difference between the scenarios (δ Q_{90}). The upper part of the table shows specific results for ten selected reservoirs, whereas the lower part shows the main statistical parameters.

Ranking	Reservoir	Scenario 1				Scenario 2				δQ_{90}
		SC (hm^3)	α (–)	Q_{90} (hm^3/yr)	Q_{90}/Q_{in}	SC (hm^3)	α (–)	Q_{90} (hm^3/yr)	Q_{90}/Q_{in}	
1	Castanhao	4982	38,184	1625.3	0.48	4650	38,977	1556.9	0.46	−4%
4	Araras	698	25,079	206.0	0.43	627	26,225	192.6	0.40	−6%
8	Pentecoste	308	59,075	90.1	0.32	286	69,023	82.9	0.29	−8%
17	Aracoiaba	127	351	38.9	0.38	115	9176	36.1	0.36	−7%
33	Lima Campos	53	56,463	4.7	0.18	49	72,754	3.5	0.13	−26%
41	Varzea Boi	42	19,664	12.1	0.23	40	20,826	11.4	0.21	−6%
52	Malcozinhado	27	17,804	8.7	0.15	24	20,604	7.6	0.13	−12%
93	Varzea Volta	9	48,542	2.9	0.05	8	67,210	2.3	0.04	−22%
111	Bonito	4.5	15,285	0.5	0.09	4.0	20,628	0.24	0.04	−50%
141	Aiuaba	0.050	1121	0.01	0.02	0.046	1423	0.007	0.01	−30%
Average (n = 141)		106	15,002	31.8	0.214	98	17,666	29.9	0.199	−6%
St dev (n = 141)		460	17,863	152.4	0.128	429	22,009	145.2	0.126	−5%
CV (n = 141)		4.34	1.19	4.79	0.583	4.36	1.25	4.86	0.633	0.896
Minimum (n = 141)		0.050	156	0.002	0.004	0.046	161	0.002	0.003	−68%
Maximum (n = 141)		4982	112,104	1625.3	0.528	4650	141,077	1557	0.519	−2%

yield. In the Brazilian drylands, water availability of surface reservoirs represents only a limited fraction of its natural river inflow, ranging typically from 20% to 50%. It is important to stress that the present analysis assumes stationary climate, i.e., both the evaporation rate and average the inflow discharge (Qin) are assumed invariant for the next three decades. If climate change is regarded, however, evaporation augmentation and inflow reduction (Krol et al., 2011) may engender even more severe impacts on water availability with time (Abbaspour et al., 2009; Faramarzi et al., 2013; Greve and Seneviratne, 2015; Donat et al., 2016; Biglarbeigi et al., 2020; Padrón et al., 2020). Table 2 shows that, on average, water availability decays by 6% for scenario 2 compared with scenario 1. For the analyzed data set, the global Q_{90} reduces from 4484 to 4216 hm^3 yr^{-1}, generating a deficit of 268 hm^3 yr^{-1}, enough to supply water to the entire State rural population.

The implementation of the water-management system in Brazil (and, in particular, in Ceará) gained credibility among the water users due to a series of factors, such as the availability of information and the organization of frequent and democratic meetings, where effective decisions are made (Campos, 2015; Taddei, 2011). In addition, the water discharge released from the reservoirs (Broad et al., 2007), considered by many the most relevant decision taken in the annual representative seminars, has been respected by the operators, with variation of 10% at the highest (de Araújo and Bronstert, 2016). Considering the fact that, with regard to water, the semiarid region is *offer constrained* (Taddei, 2011), users try to get their total demand, which is usually not possible (Salinas et al., 2019), but the committees tend to approve the annual withdrawal as high as possible, due to societal pressure (de Araújo and Bronstert, 2016). Therefore, after the implementation of the water-management system, the water outtake from the reservoirs augmented (mainly during the dry season, i.e., in the second semester), when compared with the usual withdrawal before 1993. As a consequence, in the beginning of the rainy seasons, the water reserves are lower, reducing the probability of spilling, the main mechanism of sediment outflow from surface reservoirs. This process enhances the reservoir sediment trap efficiency and, thus, the siltation rate.

In the Brazilian drylands, water users and decision makers often envisage spilling as a *waste* that should be avoided at all cost. This reasoning is focused on the premise that spill water leaves the system to reach the ocean, reducing fresh-water availability for the present and coming years. Nonetheless, spilling must be accounted for, to a certain extent, as advantageous (Kim et al., 2020; Mozafari and Zabihi, 2020).

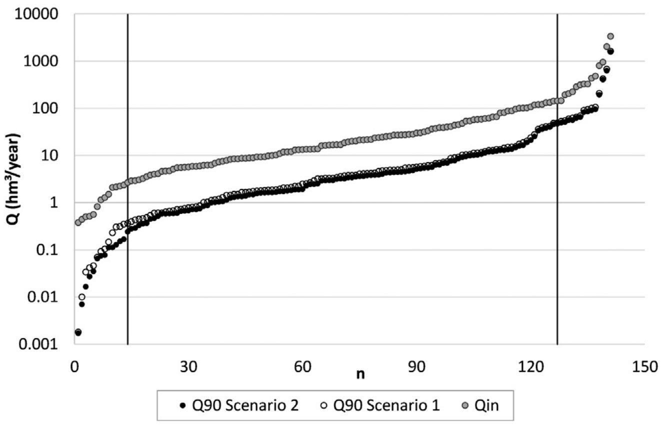

Fig. 5. Cumulative water yield with 90% reliability Q_{90} for both scenarios 1 and 2 compared with long-term average inflow Q_{in}. The X-axis represents the 141 reservoirs in ascending order. The vertical lines highlight the 14 (10%) smallest and the 14 largest reservoirs.

It expels a large amount of sediment (Garcia, 2008), extending the lifespan of reservoirs and reducing the temporal rate of water-availability curtailment (de Araujo et al., 2006). Spilling also tends to reduce water pollution. First, because it flushes pollutants from the reservoir, whereas evaporation only reduces the water content, thus, enhancing constituents concentration. Secondly, because spilling diminishes the residence time within the reservoirs, which is of paramount relevance to improve water quality (Soares et al., 2012). Another environmental problem caused by reduction of spilling is the increment of river intermittence (Barnett and Pierce, 2008; Döll and Schmied, 2012), which has considerable socio-ecological consequences (Acuña et al., 2014; Datry et al., 2018). The paradigm that spilling is simply a loss of water is erroneous and over-withdrawing reservoir water may cause serious drawbacks, including oversiltation and depletion of water quality and quantity. Besides including spilling as a partially beneficial process in the water-management system, other measures should be adopted to compensate for the water losses due to reservoirs oversiltation. First, erosion can be more effectively controlled, thus reducing sediment input to the reservoirs. There are several successful experiences of erosion control that could be applied to the State of Ceará (Rickson, 2014; Navarro-Hevia et al., 2014; Simplício et al., 2020). In fact, dos Santos et al. (2017) studied the influence of land use on sediment yield during six years in small watersheds located in Ceará. The authors observe that native Caatinga forest in the experimental site yields 124 Mg km^{-2} yr^{-1}, that the practice of burning the field enhances SY by 6%, but that the forest *thinning* reduces it by 37%.

Sediment reuse from reservoirs consists of dredging fertile sediment deposits from inside the reservoirs to make them available for agricultural production. It has proven to be a viable solution for semiarid small dams (Braga et al., 2019), which are the most vulnerable ones, and is possibly part of the solution to oversiltation of large dams, as well. The Brazilian semiarid society should also seriously implement a water-demand management system (Butler and Memon, 2005), including water reuse (Wilcox et al., 2016). These strategies can help the Brazilian dryland society adapt to decreasing water availability in the next decades (Manabe et al., 2004; Seager et al., 2013; Kumar et al., 2014; Sharafatmandrad and Mashizi, 2020).

5. Conclusions

In the Brazilian semiarid State of Ceará, artificial neural network analysis based on data from 141 monitored reservoirs show that their silting rate significantly increased after the implementation of the water management system in 1993. The *rationalization* of water use enhances withdrawal, which reduces the outflow rate and, thus, augments the reservoir sediment trap efficiency. These results attest that spill from the reservoirs cannot be seen simply as water loss, but as a positive asset, an effective mechanism that reduces siltation and improves both water quantity and quality. It is known that siltation diminishes not only the reservoir storage capacity, but also its water yield: in the study area, the 90%-reliability discharge from the reservoirs is expected to decay by 6% within 30 years, which is enough to supply water to the whole State rural population. Therefore, in the focus region, the implementation of the management system contributes to the reduction of water offer, whereas the demand is expected to increase with time. To help compensating for the water losses caused by the excessive siltation, four measures are recommended: to include reservoir spilling in the operation rules, to reduce erosion in the basins, to execute a sediment reuse policy, and to implement water-demand management.

CRediT authorship contribution statement

J.C. de Araújo: Conception and design of study, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **T. Landwehr:** Conception and design of study, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **P.H.L. Alencar:** Acquisition of data, Analysis and/or interpretation of data, Writing – review & editing. **W.D. Paulino:** Acquisition of data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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