Influence of reservoir sedimentation on water yield in the semiarid region of Brazil

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Abstract The semiarid region of Brazil (10^6 km^2) is densely populated and highly vulnerable to droughts. Governmental water policy has long been oriented towards the construction of reservoirs to reduce the impacts of droughts. Nonetheless, continuous reservoir sedimentation not only affects water quality, but also reservoir morphology, thus reducing water yield for a given reliability level. This research assesses the effect of reservoir silting on water availability in the State of Ceará. Yield-reliability curves were calculated for selected reservoirs, using a stochastic approach, in two different morphologic states. The methodology was applied to four impoundments in Ceará, where long-term (an average of seven decades) sedimentation rates were determined. The results indicate that basin management, rather than only reservoir management, is necessary to avoid substantial reductions in water-yield reliability due to regional reservoir siltation.

Key words Brazil; reservoir sedimentation; semiarid; stochastic modelling; water availability

INTRODUCTION

The northeast of Brazil is a densely populated semiarid region, with more than 20 million inhabitants in an area of approximately 10^6 km^2. It is an area characterized by a substantial water deficit (mean annual precipitation is below 900 mm year^{-1}, potential evaporation is 2200 mm year^{-1}), and recurrent droughts (see, e.g. Araújo, 1990 and Frischkorn *et al.*, 2003). To help solve this problem, the Brazilian Government created the National Department of Works Against Droughts (DNOCS, see Araújo, 1990), whose main approach has been the construction of dams.

Reservoirs are undoubtedly the most important and reliable water sources in the semiarid region of Brazil; hence, a long-term reservoir maintenance policy is strategic. Reservoir siltation is certainly one of the most important issues relative to this policy because it not only affects water availability (as pointed out in this research), but also water quality (input of contaminants, see, e.g. Walling, 1983; Fasching & Bauder, 2001; Nelson & Booth, 2002).

The main objective of this research is to propose a methodology for assessing the effect of reservoir siltation on the water availability in four watersheds in the State of Ceará, each controlled by a dam. The selected watersheds cover different climatic features (dry *sertão*, coastal, mountains, and their transitions), a wide range of

Table 1 Aspects of the four selected watersheds in Ceará.

Watershed	Area (km^2)	Climate	Annual inflow, (mm $year^{-1}$)	Cv[a]	Evaporation dry season (mm $year^{-1}$)	Source
Várzea do Boi	1221	dry, *sertão*	36	1.20[b]	1392	CEARÁ (2000)
Cedro	220	dry, *sertão*	117	1.28	1350	CEARÁ (2000)
Várzea da Volta	155	transition, *sertão*-coast	79	1.16[b]	1154[b]	Araújo *et al.* (2003)
Acarape do Meio	208	mild, mountain	138	0.66	1308	CEARÁ (2001)

[a] Cv = coefficient of variation of annual inflow.
[b] Source: this research.

catchment areas (155–1221 km^2), and reservoir capacities ($12–126 \times 10^6$ m^3) (Table 1). Sedimentation in the selected reservoirs was measured, and water yield and its associated reliability levels were computed using a stochastic approach.

METHODOLOGY

Reservoir sedimentation

Reservoir sedimentation was assessed by means of field surveys (for specific details on the methodology (e.g. Morris & Fan, 1997; Verstraeten & Poesen, 2001; Araújo & Knight, 2005). Initially, before dam construction, the morphologic characterization of their reservoirs was determined (height–area–volume curves). Then, a subsequent topographic-bathymetric survey was performed, so that any reduction in storage-capacity could be estimated. Third, core samples were taken to determine the dry bulk density of the sediment. This approach also made it possible to estimate the mass of sediment deposited during the period between the two surveys.

The reduction of storage capacity leads to changes in the morphologic parameter $\overline{\alpha}$ (equations (1) and (2); Campos, 1996) between the year of reservoir inauguration, and the year of the survey.

$$V(h) \approx \overline{\alpha} \cdot h^3 \tag{1}$$

$$\overline{\alpha} = \sum V_i \Big/ \sum \left(h_i^3\right) \tag{2}$$

$V(h)$ in equations (1) and (2) is the reservoir volume (m^3) at water level h, above the lowest reservoir level (m); and i in equation (2) is an index referring to discrete water levels.

Water yield assessment

Water yield, which can also be interpreted as water availability, is calculated as a function of the reliability level G, as presented by McMahon & Mein (1986). It can be calculated using the water balance approach as in Campos (1996). In order to calculate the actual water yield, a target water yield, and operational rules for the reservoir must be pre-determined. If the simulation period is long enough, the frequency with which the target yield is supplied, can be assumed as its reliability level.

The water balance mass conservation equation (3) can be simplified (equation (5)), assuming equation (4). Several authors accept the hypothesis engendered in equation (4) for semiarid regions (see e.g. Campos *et al.*, 1997; Ceará, 2000, 2001).

$$\mathrm{d}V/\mathrm{d}t = (Q_A + Q_H + Q_{gW}) - (Q_E + Q_S + Q_I + Q_G) \quad (3)$$

$$Q_H + Q_{gW} \approx Q_{E,w} + Q_I \quad (4)$$

$$\mathrm{d}V/\mathrm{d}t = (Q_A) - (Q_{E,d} + Q_S + Q_G) \quad (5)$$

where t is time (years), Q_A is inflow from the river network, Q_H is water input by rainfall directly on the reservoir surface, Q_{gW} is groundwater discharge to the reservoir, Q_E is water loss due to evaporation which is the sum of wet ($Q_{E,w}$) and dry season ($Q_{E,d}$) evaporation, Q_S is reservoir outflow over the spillway, Q_I is loss due to seepage to the bedrock and lateral seepage below the dam, and Q_G is the regulated water withdrawal associated with a reliability level G (all the above variables are in m^3 year^{-1}).

Equation (5) was applied separately for wet and dry seasons assuming that: (a) river inflow occurs only in the wet season; (b) therefore, spillway overflow also occurs only in the wet season, whenever the maximum storage capacity of the reservoir is surpassed; (c) water withdrawal is restricted to the dry season; and (d) water depletion in the dry season is due to simultaneous evaporation ($Q_{E,d}$) and withdrawal (Q_G).

Reservoir operating rules consist of: (a) trying to achieve the target reservoir yield, provided the water level remained above the *minimum operational volume* (set to 5% of reservoir storage capacity); and (b) if this was not possible, Q_G was adjusted iteratively so that the storage volume at the end of the dry season would be between zero and the *minimum operational volume*, provided Q_G was as close as possible to the prescribed target water yield. If Q_G was less than the target water yield, the year was viewed as unsuccessful.

Historical data in the region are scarce. Therefore, a long series (5000 years) of synthetic river inflows to the reservoir was stochastically generated using the inverse of the two-parameter gamma probability density function, as recommended by McMahon & Mein (1986) and by Campos (1996).

RESULTS AND DISCUSSION

Field survey

There appears to be a reasonably good correlation ($R^2 = 0.64$) between the reduction in the storage capacity of a particular reservoir (in its inaugural year) and the size of its catchment area (Fig. 1; Araújo *et al.*, 2003). This probably occurs because of two factors: (a) a higher catchment area for a given storage capacity usually implies a higher sediment yield; and (b) a higher storage capacity for a given catchment area usually implies an enhanced trap efficiency for sediment.

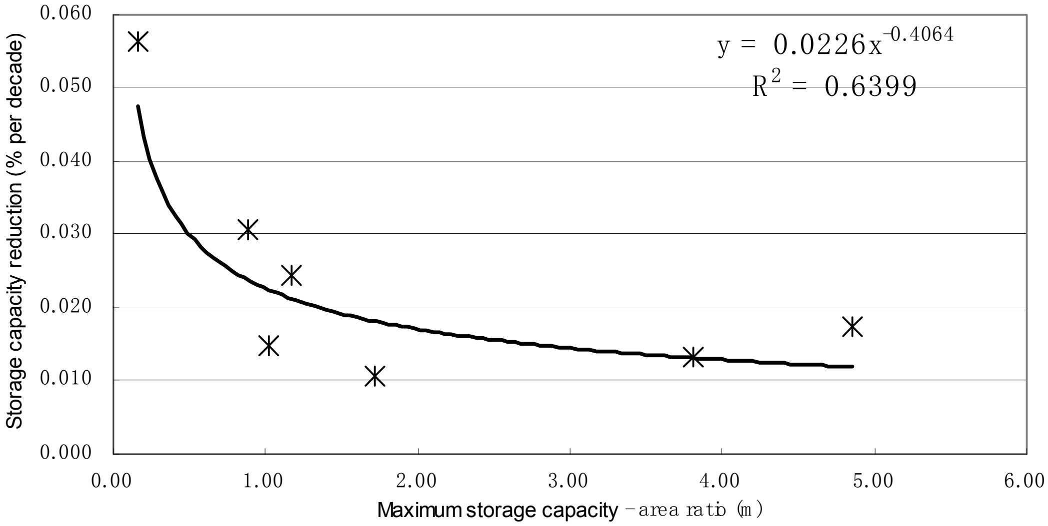

Fig. 1 Relation between storage capacity reduction and the ratio between the maximum storage capacity to catchment area for seven watersheds in the Brazilian semiarid region (Source: Araújo *et al.*, 2003).

Table 2 Reservoir sedimentation and water availability of the selected watersheds.

	Várzea do Boi	Cedro	Várzea da Volta	Acarape do Meio
Year of construction	1954	1906	1919	1924
Storage capacity S_0, hm^3	51.9	125.7	12.5	34.1
Coefficient $\overline{\alpha}$	23464	33622	11269	2115
Yield G = 99% (10^6 m^3 $year^{-1}$)	4.33	0.74	1.12	8.11
Yield G = 90% (10^6 m^3 $year^{-1}$)	10.32	5.67	2.66	11.88
Yield G = 80% (10^6 m^3 $year^{-1}$)	14.16	9.04	3.67	13.82
Yield G = 70% (10^6 m^3 $year^{-1}$)	16.62	12.17	4.39	15.46
Year of control survey	2000	2000	2000	1997
Storage capacity S_0 (10^6 m^3)	46.1	105.1	11.0	31.4
Coefficient $\overline{\alpha}$	47983	41220	21172	2412
Yield G = 99% (10^6 m^3 $year^{-1}$)	2.02	0.47	0.61	7.72
Yield G = 90% (10^6 m^3 $year^{-1}$)	7.07	4.94	2.04	11.29
Yield G = 80% (10^6 m^3 $year^{-1}$)	11.02	8.43	2.76	13.27
Yield G = 70% (10^6 m^3 $year^{-1}$)	13.32	11.27	3.50	14.88
Volume decrease (% $year^{-1}$)	0.24	0.17	0.15	0.11
Sedimentation rate (t km^{-2} $year^{-1}$)[a]	124.3	1276.6	160.9	231.8
Yield (G = 90%) decrease (% $year^{-1}$)	0.68	0.14	0.29	0.07

[a] Reservoir sedimentation per unit catchment area per unit time.

The storage capacity of the surveyed reservoirs decreased at an approximate rate of 0.2% per year (Table 2). This reduction led to a decline in water availability for two main reasons: (1) the reservoirs have less spare storage volume in the rainy season, leading to greater spillway overflows; and (2) the sedimentation process changes the morphological characteristics of the reservoir (higher $\overline{\alpha}$), leading to higher evaporative losses. Note that the reservoir-shape coefficient ($\overline{\alpha}$) did increase about 0.8% per year in the reservoirs during the observation periods (Table 2).

Impact of sedimentation on water yield

Table 2 presents the water yield corresponding to the reliability levels of 99%, 90%, 80 and 70% for the selected reservoirs. The 90%-reliability yield (Q_{90}) decreased by 0.30% per year, on average, for all reservoirs and observation periods. Individual analyses indicate that the Várzea do Boi Reservoir showed the most significant reduction in water yield (0.68% year^{-1} for G = 90%), whereas Acarape do Meio Reservoir had the least (0.07% year^{-1} for G = 90%). The low reduction of Acarape do Meio Reservoir was caused by its low sedimentation rate (watershed is relatively well preserved) and to the high hydrological efficiency of the reservoir (Q_{90} = 42% of annual inflow).

The water availability curves for the studied reservoirs are presented in Fig. 2. The impact of reservoir sedimentation on water yield can be viewed from two perspectives: (1) as a reduction of water yield for a given reliability level; or (2) as a reduction of reliability for a given yield. For example, the four reservoirs could provide 14.30 × 10^6 m^3 year^{-1} with a reliability of 99% at inauguration. After 73 years (average silting period), the 99% reliable yield was reduced to 10.82 × 10^6 m^3 year^{-1}, a decrease of 3.48 × 10^6 m^3 year^{-1} or 24%. This loss could supply almost 64 000 people, assuming consumption of 150 litres per day per capita. The same analysis for the 80% reliability level shows that the initial 40.69 × 10^6 m^3 year^{-1} water yield was reduced to 35.48 × 10^6 m^3 year^{-1} after an average of seven decades. The difference in water availability (5.21 × 10^6 m^3 year^{-1}, nearly 13%) is enough to irrigate 870 ha of maize, considering an irrigation demand of approximately 6000 m^3 ha^{-1} year^{-1} in the region. This represents

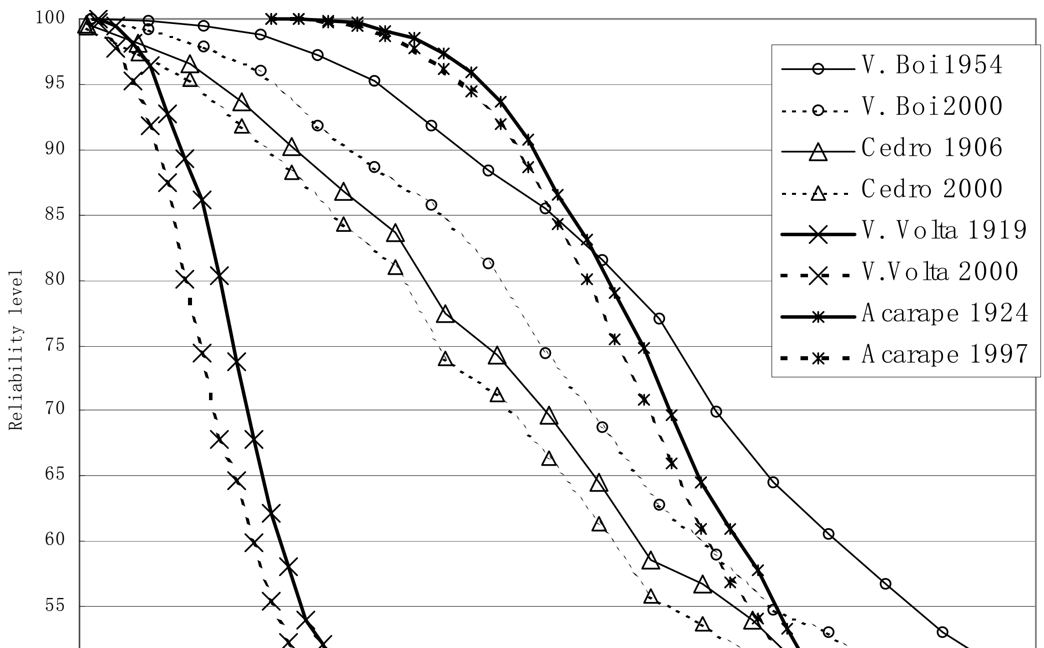

Fig. 2 Reliability level against water yield for the selected reservoirs as a function of time.

a reduction in irrigation of 12 ha of maize per year, just due to sedimentation in the four studied reservoirs. Using the second perspective, Fig. 2 shows that for the Várzea do Boi reservoir, the constant withdrawal of 10.32×10^6 m^3 $year^{-1}$ was associated with an annual reliability level of 90% in 1954, whereas in the year 2000, it decreased to 81%. In other words, the annual probability of a water shortage almost doubled (from 10 to 19%) in less than 50 years.

CONCLUSIONS

Field surveys of four reservoirs in the semiarid region of Brazil, indicated that storage capacity was reduced, on average, by almost 0.2% per year, leading to higher spillway losses due to reduced spare storage capacity at the beginning of the wet season. Reservoir morphology changed towards a more open geometry (higher values of $\overline{\alpha}$), leading to higher evaporative losses in the impoundment.

Simulations for the selected watersheds indicate that, for the average siltation period (73 years), water yield was reduced for all reservoirs, at all the reliability levels studied. Water yield with a reliability level of 99% declined by 24.3%, which is enough to supply water for almost 64 000 inhabitants. On the other hand, if a reliability level of 80% is considered, a 12.8% reduction was observed. That means that an average of 12 ha of maize irrigation would be lost every year.

The results of this research, although restricted to four reservoirs and to quantitative aspects, show the importance of sedimentation processes relative to the reduction of water availability in semiarid regions. Therefore, it is necessary for water resource management systems to consider applying a broader policy, designed to reduce erosion/sediment yield in the catchments of strategic dams, to limit losses in water yield.

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