Water availability reduction in reservoirs for different sediment yield scenarios in a semiarid watershed

José Carlos de Araújo[1]
Pedro Henrique Augusto Medeiros[2]

Abstract. The impact of anthropogenic actions on water availability is especially important in semiarid regions, where conflict for water is already a reality. In the State of Ceará, Brazil, home of 8 million inhabitants, recurrent droughts have been dealt with historically by construction of dams. Nonetheless, this approach has proven to be only a partial solution: there are about 30,000 dams in the 150,000 km² State, but the problem of water scarcity still prevails. This research evaluates the impact of different reference scenarios on reservoir silting and, therefore, on water availability in the Salgado river watershed (12,200 km² and 23 municipalities), South of Ceará. Three reference scenarios are described and their impacts assessed for the 15 largest dams in the watershed, for a five-decade period. The water yield used in the research refers to 90% annual reliability (Q_{90}). Reference scenario I assumes that sediment yield remains, for the next 50 years, the same as observed in the State for the last 50 years (de Araújo and Knight, 2004), i.e., the land-use policy would constrain the use of new areas to environmental compensation practices. Reference scenarios II and III assume that sediment yield increases proportionally to the increase of the irrigation area in the State according to IPCC scenarios A (RSA) and B (RSB), as presented by Doell and Hauschild (2002). RSA refers to "coastal boom and cash crops" and admits increasing agricultural production mainly for external markets; enhancement of tourism along the coast; and rapid GDP growth of the metropolitan area of Fortaleza. RSB, which corresponds to "decentralization and integrated rural development", assumes strengthening of medium-sized towns, extension of small-scale agro-industry, and State autonomy in relation to the Brazilian South. The water yield versus reliability simulations were performed using the VYELAS model (de Araújo, Güntner and Bronstert, 2006), based on Monte-Carlo method applied to reservoir water budget. Results for scenarios I, II and III indicate Q_{90} reduction, in the research period, of 4.5%, 14.2% and 5.5%, respectively. The difference of water availability, for a five-decade horizon, considering the most optimistic (I) and the most pessimistic (II)

[1] Associate Professor, Department of Agricultural Engineering, Federal University of Ceará, Fortaleza, Brazil, E-mail jcaraujo@ufc.br, Phone (+55 85) 3366-9757
[2] Graduate Student, Federal University of Ceará, Fortaleza, Brazil, E-mail phamedeiros@gmail.com

scenarios is 6.6 $Mm^3.yr^{-1}$, which is enough to supply water to 61 thousand inhabitants, considering per capita withdrawal of 300 litres per day. The results show that planning and implementation of a conservationist land-use policy (scenario I against scenario II) can save up to 10% of surface water yield on the long run. The research also presented the possibilities of joint use of scenarios and hydrological modelling for environmental planning.

Keywords. Water availability, reference scenarios, reservoir silting, semiarid, Brazil

Topic. 1. Water availability, use and management / 1.4. Regional sessions

1. INTRODUCTION

Water scarcity is of major concern for society. This can be even more critical in semiarid regions, where water delivery reliability is low (see, for instance, Doell and Hauschild, 2002; Salameh, 2000; Bolaane, 2000; Abu-Taleb, 2000; Ali, 1999; Aragão Araújo, 1982). Therefore, accurate assessment of water demand and its availability is essential for planners and decision-makers. For instance, de Araújo et al. (2004) studied the case of Ceará State, located in semiarid north-eastern Brazil, computing long-term water stress in its 184 municipalities from 2001 to 2025 under four scenarios. Results show that the 10% most vulnerable municipalities have an average 82% yearly expectation of water scarcity until 2025; that the mean annual probability of water shortage varies from 9% to 20%; and that between 36% and 59% of the municipalities will need intervention to prevent long-term water scarcity until 2025.

Reservoir silting can considerably reduce water availability, according to de Araújo, Güntner and Bronstert (2006): field surveys of seven basins in the Brazilian semiarid region showed that siltation reduces storage capacity by 0.24% per year. This causes reservoir morphology to change towards a more open geometry, enhancing evaporation losses. Simultaneously, capacity reduction causes uncontrolled overflow losses to increase, resulting in the reduction of water yield, i.e., of water availability. Simulations for the most critical of the seven reservoirs showed that siltation almost doubled the probability of water shortage in less than five decades. Extrapolation of these results to Ceará indicate that storage capacity in the State reduce annually by approximately 40 Mm^3, whereas total water yield with 90% reliability diminish by 0.38 $m^3.s^{-1}$ every year.

The objective of this research is, therefore, to assess, for the Salgado River basin (Ceará), the impact of reservoir siltation on water availability considering three scenarios. The 15 largest dams of the watershed were considered in the research, which used a five-decade time horizon for the analysis.

2. CHARACTERIZATION OF THE FOCUS AREA

Northeast Brazil is a semiarid region with ephemeral rivers and negligible groundwater reserves. In addition, the high inter-annual rainfall variability leads to the occurrence of droughts, with serious social-economic consequences. Construction of dams has historically been the main alternative to supply water to the local population, allowing the storage of water through the dry periods (Aragão Araújo, 1982). Nonetheless, the water stored superficially is very susceptible not only to loss due to the high evaporation rates (up to 2,500 mm/year), but also to reservoirs silting. In the Federal State of Ceará, that occupies an area of 150,000 km², the number of existing dams lay around 30,000. De Araújo et al. (2004) argue that such reservoirs are responsible for 90% of the water supply to the local population (8 million inhabitants in the year 2000), but such reservoirs are subjected to a storage capacity reduction due to sediment yield in the catchment areas.

The impact of reservoir silting in water yield reduction was assessed in this study for the Salgado river watershed, State of Ceará (see Figure 1). The watershed drains an area of approximately 12,200 km², which represents 8% of the State area; is located within coordinates 6°16’8” and 7°51’41” of latitude South and 38°31’9” and 39°44’30” of longitude West; has an average precipitation of 900 $mm.yr^{-1}$; and annual potential evaporation of 2,000 mm. Twenty-three municipalities are located in its catchment area, with a population of 760,000 inhabitants. The intra-annual rainfall variability defines two periods with very distinct climatic characteristics: a wet period, comprehending the months of January to April (over 70% of the mean annual rainfall), and a long dry period from May to December. River flow follows the tendency of rainfall, with high temporal concentration during the wet period. Figure 2 shows monthly averaged river flow in the Icó section near the confluence of Salgado and Jaguaribe rivers.

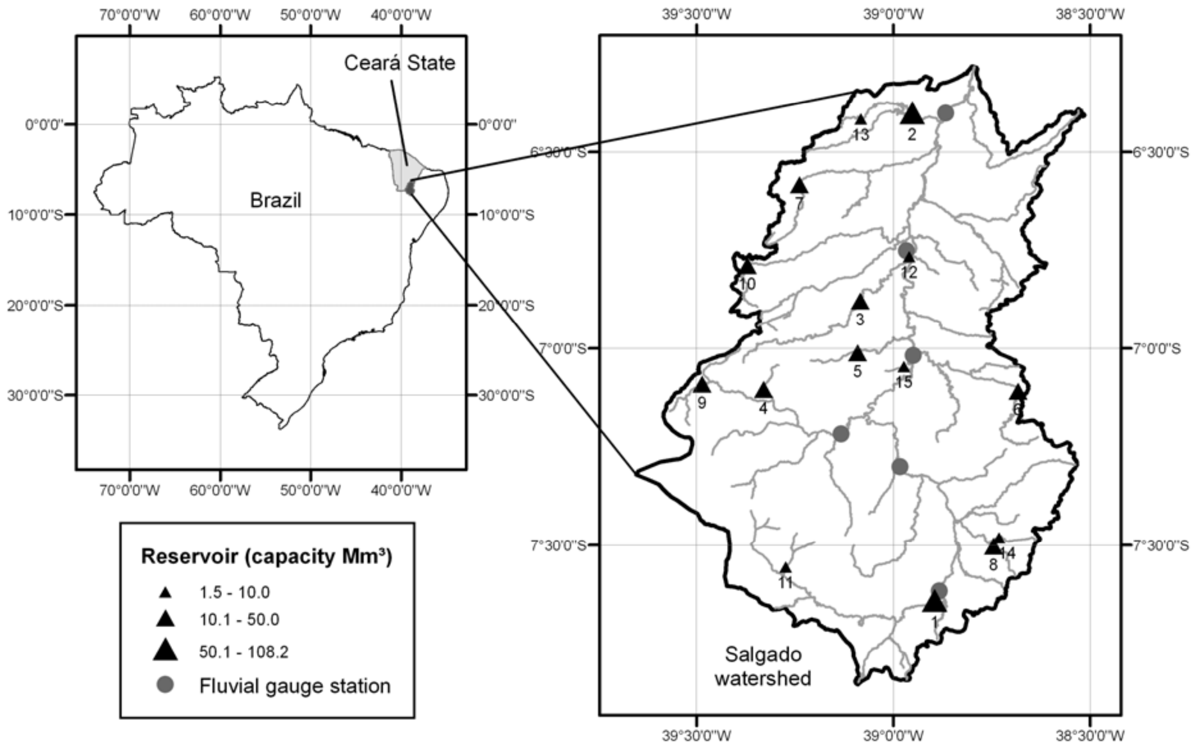

Figure 1. Location of the Salgado basin, Northeast Brazil, its main reservoirs and fluvial gauge stations

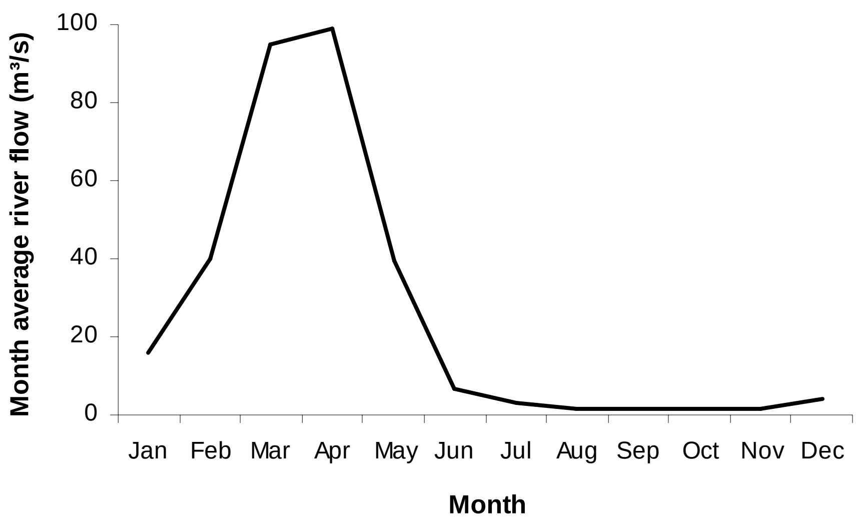

Figure 2. Monthly average river discharge in the Icó section (1957-2005)

Reservoirs in the Salgado basin - as in the entire State - are numerous, but only 15 have storage capacity superior to 1.0 Mm³, being responsible for most of the water supply with high reliability level. These reservoirs, whose main characteristics are presented in Table 1, can store almost 500 Mm³. Figure 1 illustrates a location map of the study area with the position of the reservoirs analyzed in this study.

Table 1. Reservoirs with storage capacity greater than 1 Mm³ in the Salgado river watershed

Size order	Reservoir	Catchment area (km²)	Capacity (Mm³)	Mean inflow* (Mm³/year)
1	Atalho	1,796.3	108.2	84.3
2	Lima Campos	409.2	66.3	17.8
3	Rosário	332.2	47.2	14.4
4	Manoel Balbino	44.6	37.1	1.9
5	Cachoeira	72.6	34.3	3.1
6	Prazeres	146.2	32.5	6.3
7	Ubaldinho	168.0	31.8	7.2
8	Quixabinha	85.2	31.7	3.6
9	Umari	112.2	28.7	4.8
10	Olho d'Água	73.1	21.0	3.1
11	Taquari	111.6	9.0	4.8
12	Estrema	26.3	2.9	1.1
13	Tatajuba	22.5	2.7	1.0
14	Gomes	31.2	2.3	1.3
15	Mocó	14.9	1.5	0.6

* Estimated from data of six fluvial gauge stations in the Salgado watershed

3. MATERIAL AND METHODS

3.1. Scenarios construction. The research was based on comparison of an initial and a final situation for three reference scenarios. The initial situation for all reservoirs considered the morphology of the dams in the construction year, as if they had been built simultaneously. The final situation corresponded to a five-decade time horizon. For each reference scenario, the storage capacity of the reservoirs varied according to the expected silting rate, whereas the remaining variables, such as annual inflow and climate characteristics, were maintained constant in the simulations. Scenario I admits that sediment yield remains, for the next 50 years, the same as observed in seven basins in the State during the XX Century (de Araújo, 2003; de Araújo and Knight, 2004). Field measurements indicated that silting is approximately 0.24% per year, value admitted for scenario I. It means that land use in the Salgado River basin would either remain in the present level or further land use would only be authorized should environmental practices be performed as compensation. Reference scenario II assumes that sediment yield increases proportionally to the irrigation area in the State according to IPCC scenario A of Doell and Hauschild (2002). This scenario admits "coastal boom and cash crops". In scenario II the agricultural production is mainly directed towards the external markets; tourist activities would be relevant along the coast; and the GDP would rapidly grow in the metropolitan area of Fortaleza, the State capital. In average, silting for the next 50 years in scenario II would occur at a rate of 0.63% per year. Reference scenario III also assumes that sediment yield increases proportionally to the irrigation area, but according to IPCC scenario B of Doell and Hauschild (2002), which corresponds to “decentralization and integrated rural development”. Scenario III corresponds to economic and social strengthening of medium-sized towns, extension of small-scale agro-industry to provide food and input to local demand, and State autonomy in relation to the more industrialized Brazilian South. Average silting rate for scenario III is 0.31% per year.

3.2. Hydrological data. The rainfall and evaporation data were taken from the data-base of the State Meteorological and Water Resources Foundation (www.funceme.br). River discharge data were taken from the six gauge stations of the National Water Agency (www.ana.gov.br) shown in Figure 1. For the basins without direct river discharge measurements, regression equations (1) and (2) were used to assess mean discharge (Q) and the respective annual coefficient of variation (Cv).

$$Q(\text{mm.yr}^{-1}) = 0.0025 \cdot A(\text{km}^2) + 42.442 \qquad (1)$$

$$Cv = 2 \cdot 10^{-5} \cdot A(\text{km}^2) + 0.8465 \qquad (2)$$

3.3. Water yield simulation. Reduction of water availability due to reservoir silting was assessed in the Salgado River basin using simultaneous water balance simulation of its 15 largest reservoirs. The simulations were performed with VYELAS model (de Araújo, Güntner and Bronstert, 2006). The method consists of simulating long-term water balance (Equation 3) for different reservoir sizes, computing its respective planning water yield Q_{90}, i.e., the withdrawal discharge with 90% annual reliability (McMahon and Mein, 1986).

$$\frac{\Delta V(t)}{\Delta t} \cong \left(\overline{Q}_R\right) - \left(\overline{Q}_{ED} + \overline{Q}_W + \overline{Q}_O\right) + \delta Q \qquad (3)$$

$$V(m^3) \cong \alpha \cdot y^{3.0} \qquad (4)$$

In Equation (3), V = reservoir volume; t = time; Q_R = river inflow discharge; Q_{ED} = evaporation discharge from the lake in the dry season; Q_W = water yield; Q_O = overflow discharge; and δQ = difference between remaining inputs (rainfall direct on the lake and groundwater) and remaining outputs (infiltration and evaporation from the lake in the wet season). The term δQ is admitted negligible for long-term simulations (Campos, 1996; de Araújo et al., 2006). Stage-volume was represented by Equation (4), in which “y” represents water height (m) and “α” is the shape parameter. Surface-reservoir water balance is simulated on a seasonal basis, considering lake evaporation, uncontrolled weir outflow and water withdrawal, which depends on its operational rule. To simulate the water balance, a long-term 10,000-year synthetic series of river discharge is stochastically generated using historical average and standard-deviation of annual river discharges. A stochastic variable is computed using a random seed and a probability density function, in this case, the two-parameter gamma function (de Araújo et al., 2006). The water balance simulation is repeated for different withdrawal discharges. For each withdrawal discharge the reliability is computed.

4. RESULTS AND DISCUSSION

The results are expressed as yield-reliability curves (Figure 3) for the entire Salgado river basin, i.e. considering all 15 main reservoirs simulated. By a comparison of the curves for the reference scenarios with that for the original situation, water yield reduction due to reservoir silting can be assessed. It is observed that reference scenarios I (restriction in the use of new areas) and III (decentralization and integrated rural development) produce similar impacts on water yield, with mean reduction (for 50 years) of 5.5% and 6.5%, respectively. For reference scenario II (coastal boom and cash crops) water yield reduction is more pronounced, of 13.6% in average. A more detailed evaluation was carried out for the 90% reliability level, which is a standard level for planning purposes. Table 2 presents water yield with 90% reliability (Q_{90}) to all 15 simulated reservoirs in their original situation and considering the reference scenarios. Also, the relations between water yield to the reference scenarios and the original values are presented. Another analysis approach is the comparison of scarcity probability for the different scenarios. For instance, the 15 reservoirs could provide 69 $Mm^3.yr^{-1}$ with 90% reliability level in the original situation. For scenarios I and III reliability would be reduced to 88%, whereas for scenario II it would be reduced to 83%. To understand the meaning of the reliability reduction, the risk of water scarcity to provide 69 $Mm^3.yr^{-1}$ within 20 year in the initial situation would be 88%; for scenarios I and III 92%; whereas for scenario III it is as high as 98%.

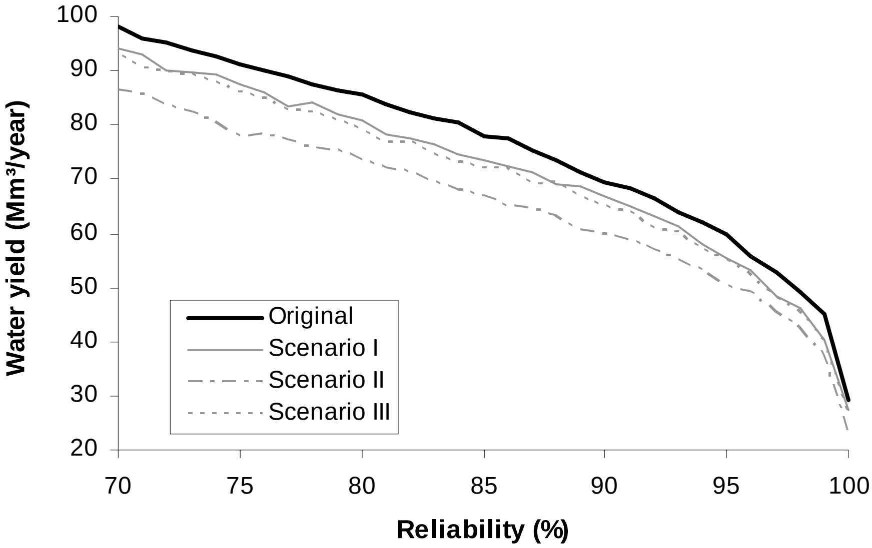

Figure 3. Yield – reliability curves for the original situation and for the three reference scenarios. The curves refer to the summation of the yield in the 15 largest reservoirs of the Salgado basin.

Table 2. Results of water yield simulations for scenarios Sc I, Sc II and Sc III for a five-decade period. The table presents the original value of Q_{90} as in the year of construction (original) and five decades later according to the reference scenario.

Size order	Reservoir name	Cumulative Q_{90}	Q_{90} ($Mm^3.yr^{-1}$) Original	Sc I	Sc II	Sc III	$Q_{90}(Sc)/Q_{90}$ original Sc I	Sc II	Sc III
1	Atalho	58.7%	40.3	37.6	32.3	37.0	0.93	0.80	0.92
2	L. Campos	67.8%	6.2	6.2	5.8	6.2	1.00	0.94	0.99
3	Rosário	76.4%	6.0	5.9	5.5	5.9	0.98	0.91	0.98
4	M. Balbino	77.0%	0.4	0.4	0.4	0.4	1.00	1.00	1.00
5	Cachoeira	77.9%	0.6	0.6	0.6	0.6	1.00	1.00	1.00
6	Prazeres	83.9%	4.1	4.1	3.9	4.1	0.99	0.95	0.99
7	Ubaldinho	87.4%	2.4	2.4	2.3	2.4	0.99	0.97	0.99
8	Quixabinha	89.8%	1.6	1.6	1.6	1.6	1.00	1.00	1.00
9	Umari	92.9%	2.1	2.1	2.1	2.1	1.00	0.99	1.00
10	O. d'Água	94.4%	1.1	1.1	1.1	1.1	1.00	1.00	1.00
11	Taquari	97.7%	2.3	2.1	1.9	2.1	0.93	0.85	0.93
12	Estrema	98.3%	0.4	0.4	0.4	0.4	0.95	0.90	0.94
13	Tatajuba	98.9%	0.4	0.4	0.3	0.4	0.97	0.89	0.97
14	Gomes	99.7%	0.6	0.6	0.5	0.6	0.99	0.90	0.99
15	Mocó	100%	0.2	0.2	0.1	0.2	0.94	0.82	0.89
	Total		68.7	65.6	58.9	64.9	0.96	0.86	0.95

Results indicate that the impact of reservoir silting in water yield is strongly influenced by land use. If scenario II prevails, in which a strong economic development of the metropolitan area of Fortaleza occurs and the production of cash crops is dominated by large companies aiming the external markets, water yield with 90% reliability can be reduced by 14.2% in 50 years. Nonetheless, if a decentralization scenario occurs with strengthening of medium-sized towns and predominance of small-scale agro-industry (scenario III), reduction of water yield is only 5.5% in the same period. A similar trend (water yield reduction of 4.5%) is expected if environmental practices are adopted in order to restrict sediment yield on the next 50 years to the same as observed in Ceará State for the last 50 years (scenario I) according to de Araújo and Knight (2004). The difference of water availability, for a five-decade horizon, considering the least (I) and the most critical (II) scenarios is 6.6 $Mm^3.yr^{-1}$. This is enough to supply water to 61 thousand inhabitants, considering per capita withdrawal of 300 litres per day.

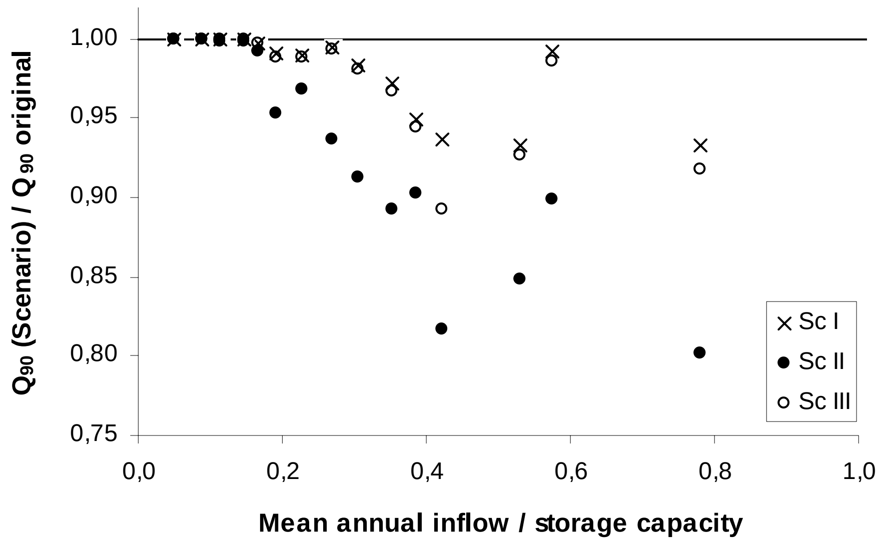

Figure 4. Q_{90} reduction as a function of residence period (yr^{-1}), given by division of mean annual inflow ($Mm^3.yr^{-1}$) per storage capacity (Mm^3) for the 15 reservoirs analyzed and for the three scenarios

Figure 4 illustrates the Q_{90} reduction, expressed as the relation of Q_{90} in the reference scenarios and the original Q_{90}, related to residence period (overflow index), i.e. a large residence period indicates that the reservoir overflows more often. It is observed that reservoirs with low overflow index show very low water yield reduction, since most of the water is stored in the reservoir independent of the scenario. Nonetheless, in the reservoirs with high overflow index, in which a large amount of water is lost due to overflow, a reduction in the storage capacity produces higher water yield reduction. From Figure 4 it can be drawn that scenario II is the one with the lowest water availability for all overflow index range after five decades. Another observation from Figure 4 is that water availability reduction is much more sensible for the reservoirs with high residence period, whereas for the reservoirs with residence period lower than 0.2 yr^{-1}, water yield reduction is negligible due to silting.

5. CONCLUSIONS

From the research, the following conclusions can be drawn:

i. The applied method allowed assessing the water availability reduction due to siltation for three scenarios in five decades for the 15 largest reservoirs of the Salgado river basin (12,200 km^2);
ii. Reference scenarios I (conservation policy) and III (decentralization and integrated rural development) produce similar impacts on water availability, with mean reduction, for 50 years, of approximately 6%;
iii. Reference scenario II (coastal boom and cash crops) caused water yield reduction of more than double of the remaining scenarios (almost 14% in average);
iv. The method also allowed assessment of reliability reduction for a certain water withdrawal from the system: annual risk of shortage of 69 $Mm^3.yr^{-1}$ increased from 10% in the original situation to 17% for scenarios II;
v. The difference of water availability, for the analysis horizon, considering the least (I) and the most critical (II) scenarios is enough to supply water to 61,000 inhabitants;
vi. Water availability reduction is much more sensible for the reservoirs with high residence period;
vii. Water yield reduction due to silting in reservoirs with residence period lower than 0.2 yr^{-1} is negligible;
viii. Implementation of a conservationist land-use policy (scenario I against scenario II) can save up to 10% of surface water yield in five decades.

ACKNOWLEDGEMENTS

The authors are grateful to CAPES - the Brazilian Coordination of Qualification of Superior Level Personal - for the Doctorate scholarship of the second author, and to CNPq - the Brazilian Research Council - for the financial support of the ANDICE project (CNPq-PQ, process 301135/2005-3).

REFERENCES

Abu-Taleb, M.F., 2000. Impacts of global climatic change scenarios on water supply and demand in Jordan. *Water International*, 25(3): 457-463, September.

Ali, S.H., 1999. Water scarcity and institutional reform in southern Africa. *Water International*, 24(2): 116-125, June.

Aragão Araújo J.A., 1982. *Dam in the Northeast of Brazil*. DNOCS, Fortaleza, Brazil, 120 p.

Bolaane, B., 2000. Towards sustainable management of scarce water resources in Botswana. *Water International*, 25(2): 246-252, June.

Campos, J.N.B., 1996. *Reservoirs design* (in Portuguese). Ed. UFC. Federal University of Ceará, Fortaleza, Brazil, 51 p.

de Araújo, J.C., 2003. Reservoirs silting in the semiarid region: modelling and validation (in Portuguese). *Revista Brasileira de Recursos Hídricos*, 8(2): 39-56.

de Araújo, J.C., Döll, P., Güntner, A., Krol, M., Abreu, C.B.R., Hauschild, M., Mendiondo, E.M., 2004. Water scarcity under scenarios for global climate change and regional development in semiarid Northeastern Brazil. *Water International*, 29(2): 209-220.

de Araújo, J.C., Knight, D.W., 2004. Assessment of sediment yield of watersheds by reservoir survey and simulation modelling in Brazilian semiarid environment. In: Geomorphological processes and human impact in river basins, 2005, Solsona. Proceedings. Wallingford: *IAHS Publication*, 299: 126-131.

de Araújo, J.C., Güntner, A., Bronstert, A., 2006. Loss of reservoir volume by sediment deposition and its impact on water availability in semiarid Brazil. *Hydrological Sciences Journal-Journal des Sciences Hydrologiques*, 51(1): 157-170, DOI 10.1623/hysj.51.1.157.

Döll, P., Hauschild, M., 2002. Model-based regional assessment of water use: an example for semi-arid Northeastern Brazil. *Water International*, 27(3): 310-320.

McMahon, T.A., Mein, R.G., 1986. *River and reservoir yield*. Water Resources Publications, Littleton, Colorado, USA, 368 p.

Salameh, E., 2000. Redefining the water poverty index. *Water International*, 25(3): 469-473, September.