
Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: www.tandfonline.com/journals/thsj20

# Loss of reservoir volume by sediment deposition and its impact on water availability in semiarid Brazil

JOSÉ CARLOS DE ARAÚJO, ANDREAS GÜNTNER & AXEL BRONSTERT

# Loss of reservoir volume by sediment deposition and its impact on water availability in semiarid Brazil

**JOSÉ CARLOS DE ARAÚJO**[1], **ANDREAS GÜNTNER**[2] & **AXEL BRONSTERT**[3]

1 *Department of Hydraulic and Environmental Engineering, Federal University of Ceará, Campus do Pici, bl. 713, 60.451-970 Fortaleza CE, Brazil*
jcaraujo@ufc.br

2 *GeoForschungsZentrum Potsdam (GFZ), Section 5.4: Engineering Hydrology, Telegrafenberg, D-14473 Potsdam, Germany*

3 *Institut für Geooekologie, Universität Potsdam, Postfach 60 15 53, D-14415 Potsdam, Germany*

**Abstract** A methodology is presented to assess the impact of reservoir silting on water availability for semiarid environments, applied to seven representative watersheds in the state of Ceará, Brazil. Water yield is computed using stochastic modelling for several reliability levels and water yield reduction is quantified for the focus areas. The yield–volume elasticity concept, which indicates the relative yield reduction in terms of relative storage capacity of the reservoirs, is presented and applied. Results show that storage capacity was reduced by 0.2% year$^{-1}$ due to silting, that the risk of water shortage almost doubled in less than 50 years for the most critical reservoir, and that reduction of storage capacity had three times more impact on yield reduction than the increase in evaporation. Average 90% reliable yield–volume elasticity was 0.8, which means that the global water yield ($Q_{90}$) in Ceará is expected to diminish yearly by 388 L s$^{-1}$ due to reservoir silting.

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

## Perte de volume de stockage en réservoirs par sédimentation et impact sur la disponibilité en eau au Brésil semi-aride

**Résumé** L'article présente une méthodologie pour évaluer l'impact de l'envasement des réservoirs sur la disponibilité en eau en contextes semi-arides, et son application à sept bassins versants représentatifs de l'État du Ceará, au Brésil. La fourniture d'eau est calculée par modélisation stochastique pour plusieurs niveaux de fiabilité et la réduction de la fourniture d'eau est quantifiée pour la zone d'étude. Le concept d'élasticité fourniture–volume, qui est indicatif de la réduction relative de la fourniture d'eau en termes de capacité relative de stockage des réservoirs, est présenté et appliqué. Les résultats montrent que la capacité de stockage a diminué de 0.2% an$^{-1}$ à cause de l'envasement, que le risque de pénurie d'eau a doublé en moins de 50 ans, et que l'impact de la diminution de la capacité de stockage sur la fourniture d'eau est trois fois plus important que celui de l'augmentation de l'évaporation. L'élasticité fourniture–volume moyenne est de 0.8 pour une fiabilité de 90%, ce qui signifie que la fourniture globale d'eau ($Q_{90}$) dans l'Etat du Ceará devrait diminuer de 388 L s$^{-1}$ chaque année en raison de l'envasement des réservoirs.

**Mots clefs** Brésil; réservoir; sédimentation; région semi-aride; modélisation stochastique; disponibilité en eau

## INTRODUCTION

Water availability and the associated risk of failure of water supply are of major concern in water resources management, especially in semiarid regions subject to conflicts between water uses and users. Water scarcity is usually associated with natural extreme events, such as droughts, but anthropogenic processes also affect the water availability. It is, therefore, necessary to understand such processes and to quantify their consequences, so that long-term sustainable policies can be applied to watersheds, reducing the risk of water stress. Reservoirs are commonly the most important water sources with acceptable reliability in semiarid regions and society strongly depends on their sustainability (Araújo *et al.*, 2005). Nonetheless, various

*Open for discussion until 1 August 2006* 

social and economic activities in the watersheds may generate impacts that will reduce water availability in the reservoirs, in both quantitative and qualitative aspects. Additional problems may arise through the delivery of sediment and sediment-associated contaminants (Walling, 1983; Lane *et al*., 1997; Fasching & Bauder, 2001; Nelson & Booth, 2002; Liénou *et al*., 2005). The main objective of this research was to propose a methodology to assess the effect of reservoir sedimentation on water availability in a semiarid region using a stochastic approach, such as in Hantush & Kalin (2005). The methodology was applied to seven catchments of different sizes, physiographic characteristics and conservation status in the semiarid State of Ceará, Brazil (see Table 1).

## DESCRIPTION OF THE STUDY AREA

The Brazilian semiarid region (Fig. 1) has an area of one million km$^2$ and a population above 20 million inhabitants, including nine federal states. It is characterized by a strongly negative atmospheric water balance (average precipitation below 900 mm year$^{-1}$, and potential evaporation above 2200 mm year$^{-1}$), limited groundwater resources (fissured aquifers prevail), shallow soils and recurrent droughts, leading to a highly vulnerable natural water resources system. Conflicts for water use in the Brazilian semiarid region have occurred for centuries (Araújo, 1990), and governmental intervention has strongly relied on the construction of a reservoir network. According to Araújo (1990), the State of Ceará (150 000 km$^2$) has more than 93% of its area in the drought polygon, i.e. in the semiarid region (Fig. 1). The representative watersheds that were selected

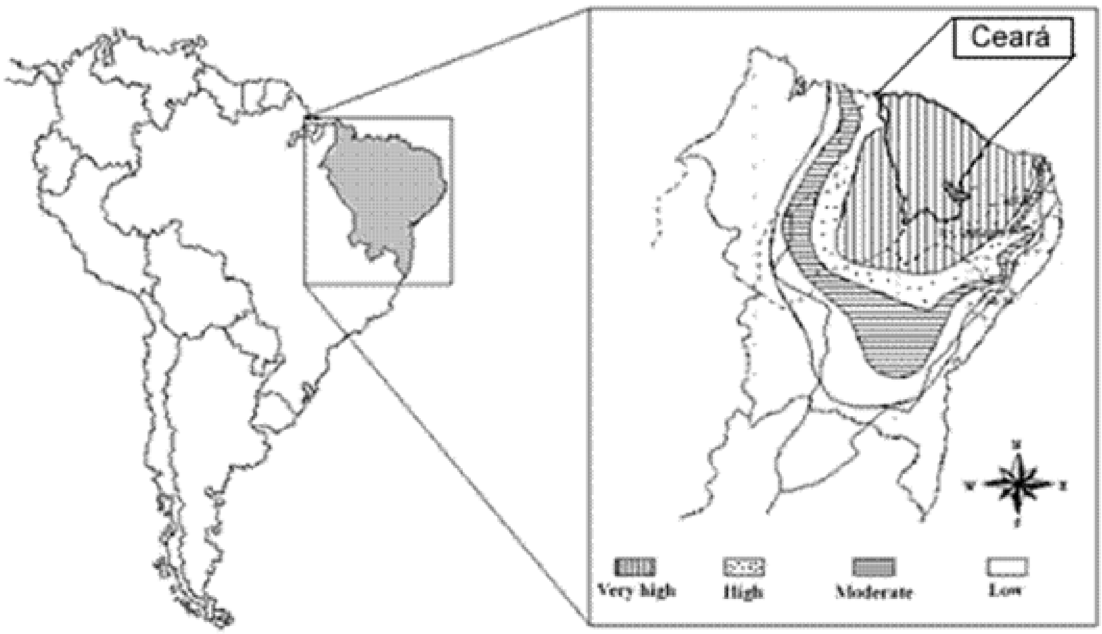


**Fig. 1** Location of the Brazilian semiarid region and Ceará in relation to Brazil and South America. The iso-lines refer to the probability of droughts, according to Araújo (1990).

**Table 1** Characteristics of the selected watersheds in Ceará, Brazil.

| Watershed (named after the outlet reservoir) | Catch-ment area ($km^2$) | Climate / land use | Average annual inflow (mm $year^{-1}$) | *Cv* [a] | Evaporation dry season (mm $year^{-1}$) | Resi-dence time (year) [e] | Source of hydrological data |
|---|---|---|---|---|---|---|---|
| Várzea Boi | 1221 | dry, *sertão* / rural | 36 | 1.20 [b] | 1392 | 1.17 | SRH (2000) |
| Cedro | 220 | dry, *sertão* / rural | 117 | 1.28 | 1350 | 4.86 | SRH (2000) |
| Canabrava | 2.9 | transition, *sertão*-mountain / rural | 112 | 0.96 [b] | 1155 [c] | 3.81 | Araújo *et al.* (2003) |
| Várzea Volta | 155 | transition, *sertão*-coast / rural | 79 | 1.16 [b] | 1.154 [(2)] | 1.02 | Araújo *et al.* (2003) |
| S. Anastácio | 7.8 | mild, coast / completely urban since late 1960s | 410 | 0.80 [b] | 1029 [d] | 0.16 | Oliveira (1999) |
| S. Mateus | 229 | dry, *sertão* / rural | 51 | 1.41 | 1350 | 0.88 | SRH (1996) |
| Acarape | 208 | mild, mountain / rural with minor urban contribution | 138 | 0.66 | 1308 | 1.19 | SRH (2001) |

[a] *Cv* = coefficient of variation of annual inflow.
[b] Source: this research.
[c] Set equal to Thomas Osterne Reservoir (SRH, 2000).
[d] Source: Departamento Nacional Meteorologia (1992).
[e] Storage capacity divided by mean annual inflow.

(Table 1) cover the main climate features (from the dry inner land—or *sertão*—to the relatively mild coast), rural and urban environments, as well as a wide range of catchment areas (3–1221 $km^2$) and reservoir capacities (0.5–126 $Mm^3$). Further information on the area can be found elsewhere (Araújo, 1990; Gaiser *et al.*, 2003; Güntner *et al.*, 2004).

## METHODOLOGY

### Field survey

The first step consisted of accomplishing a recent morphological characterization of the selected reservoirs by means of topographic and bathymetric surveys, resulting in height–area–volume curves (e.g. Morris & Fan, 1997; Verstraeten & Poesen, 2001). The surveys were usually carried out at the end of the dry season, which coincided with the lowest water level and, thus, enhanced measurement accuracy, once topographic surveys are more accurate than bathymetry. The updated morphology was then compared to that based on topography before the construction of each dam using the approach presented by Campos (1996). This allowed quantification of the reduction in storage capacity due to reservoir sedimentation as well as changes in the morphologic parameter $\overline{\alpha}$, as defined in equations (1) and (2) below, between both years of reference (years of reservoir inauguration and of recent survey):

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

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

where $V(h)$ is the reservoir volume ($m^3$) at the water level $h$ above the lowest reservoir level (m), and $i$ is an index referring to discrete water levels. An increase in $\overline{\alpha}$ between two reference years indicates that the reservoir becomes shallower and morphologically more open, hence evaporation losses are expected to increase. The dry bulk density of the sedimentation within the reservoirs was obtained through core sampling campaigns. This allowed the estimation of the mass of sediment retained in the reservoirs between the reference years (for more information on the field surveys, see Araújo & Knight, 2005).

## Water availability assessment

In order to assess water availability, the reservoir water yield and its associated reliability level $G$, i.e. the long-term probability of success in providing the water yield during one year (see McMahon & Mein, 1986), was computed for both reference years. For this purpose, the stochastic experimental method developed by Campos (1996; see also Campos *et al.*, 1997) for semiarid environments was used. It consists of calculating a simplified reservoir water balance with seasonal time steps for the wet and dry seasons and for a given reservoir operation rule. A simple frequency analysis allows estimation of reliability levels, which can be associated with a prescribed target reservoir yield, defined by the users' water demands. For the simulation, the initial water volume in the reservoir was set to the minimum value of half the storage capacity and half the mean annual inflow. The water balance in the reservoirs was calculated by simplifying equation (3) under hypothesis (4), which led to equation (5):

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

$$Q_H + Q_{gW} \approx Q_{E,w} + Q_I \tag{4}$$

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

where $t$ is time (year); $Q_A$ 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 above variables are in $m^3$ year$^{-1}$).

For calculating the reservoir water balance separately for the wet and dry seasons, the method accounted for the fact that river inflow occurs only in the wet season (in semiarid Brazil, usually about five months in the first semester), followed immediately by spillway overflow whenever the maximum storage capacity of the reservoir is surpassed. No water withdrawal was considered in the wet season, because of the considerable reduction in water demand observed in this period. Thus, at the end of the wet season, the reservoir level was given by the initial volume plus river inflow minus spillway overflow. The dry season was characterized by volume depletion due to simultaneous evaporation ($Q_{E,d}$) and withdrawal ($Q_G$). The reservoir volume at the end of the year was calculated as the volume at the end of the wet season minus evaporation losses and withdrawal. The reservoir operation rule applied for the simulations is illustrated in Fig. 2. It basically consists of defining the annual water with-

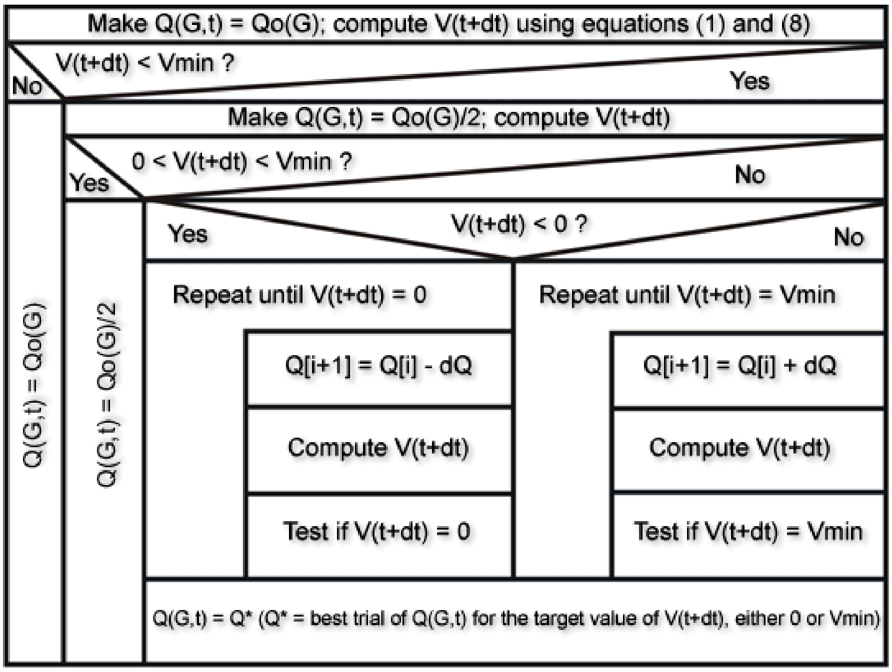


**Fig. 2** Algorithm of the reservoir operation rule in the dry season. *Q*: withdrawal discharge; *Q*[*i*]: *i*th iteration of *Q*; *Q*o(*G*): target water yield associated to reliability level *G*; *V*min: minimum operational volume, admitted 5% of maximum storage capacity; $V(t + \mathrm{d}t)$: reservoir volume in the end of the dry season; d*Q*: increment/ decrement in withdrawal discharge.

drawal volume $Q_G$ or effective reservoir yield, which, in a first step, was set equal to the target reservoir yield as defined by the users' water demand. For years in which $Q_G$ would reduce the reservoir storage volume at the end of the dry season to values below the minimum operational volume, which was set to 5% of reservoir storage capacity, $Q_G$ was adjusted in a second step by an iterative procedure. This adjustment was done with the objective of giving a storage volume at the end of the dry season between zero and the minimum operational volume, while at the same time setting $Q_G$ to a value as close as possible to the prescribed target water yield (Fig. 2). If the final $Q_G$ was less than the target water yield, the year was considered unsuccessful. The reliability level $G$ was then given by $G = 1 - (N_U/N)$ where $N_U$ is the number of unsuccessful years and $N$ the total number of years in the simulation.

River inflow to the reservoir is generated by a stochastic procedure, using the inverse of the two-parameter gamma probability density function (McMahon & Mein, 1986; Campos, 1996). The parameters of the distribution were derived from the mean and standard deviation of historical annual inflow to the reservoir. A 5000-year synthetic series was generated for each watershed, which reproduced the historical mean and the coefficient of variation of annual inflow as given in Table 1. In order to simulate the water balance in the dry season, a simplified implicit method was used based on the mass conservation principle in the dry season:

$$\mathrm{d}V / \mathrm{d}t = -Q_{E,d} - Q_G \qquad (6)$$

$$A \cdot \frac{\mathrm{d}h}{\mathrm{d}t} = -A \cdot \frac{\mathrm{d}E_d}{\mathrm{d}t} - Q_G \qquad (7)$$

where $A$ is the reservoir water surface area (m$^2$) and $E_d$ is the evaporation rate in the dry season (m year$^{-1}$). Considering equation (1), $A$ (= d$V$/d$h$) can be approximated by $A \approx 3 \cdot \overline{\alpha} \cdot h^2$. Multiplying equation (7) by d$t$, integrating after time from the beginning to the end of the dry season, and substituting instantaneous $A$ by average area during the dry season $\overline{A} \approx (3/2) \cdot \overline{\alpha} \cdot (h_t^{\ 2} + h_{t+\Delta t}^{\ \ 2})$, results in:

$$h_{t+\Delta t}^3 + (3/2) \cdot h_{t+\Delta t}^2 \cdot E = h_t^3 - (3/2) \cdot h_t^2 \cdot E - (Q_G / \overline{\alpha}) \cdot \Delta t \tag{8}$$

where the index $t$ refers to the beginning of the dry season and $t + \Delta t$ to its end, and the only unknown, for a given $Q_G$, is the final height $h_{t+\Delta t}$, which can easily be obtained numerically. From this, the storage volume at the end of the dry season can be computed using equation (1).

## Yield–volume elasticity

In order to interpret the results in a more systematic way the yield–volume elasticity ($\varepsilon$) concept is proposed (equation (9)), in which $S$ is the storage capacity of the reservoir:

$$\varepsilon_G = \frac{\mathrm{d}Q_G / Q_G}{\mathrm{d}S / S} \tag{9}$$

The elasticity $\varepsilon$ represents the relative impact of the reduction in reservoir storage capacity on yield reduction, for a given reliability level $G$, and can be useful for extrapolation of yield–volume reduction results. Therefore, the higher $\varepsilon_G$, the stronger will be the impact of sedimentation on water yield reduction. It is important to note that the reduction of water yield due to the silting process is mainly caused by two factors: (a) the reduction in storage capacity (which leads to an increase in spillway overflow losses) and (b) the morphological changes in the reservoir (mathematically represented by changes of $\overline{\alpha}$, where larger $\overline{\alpha}$ leads to higher evaporation losses). Assuming $\varepsilon_G$ to be a constant value in time and integrating equation (9) leads to:

$$\varepsilon_G = \frac{\ln(S / S_0)}{\ln(Q_G / Q_{G,0})} \tag{10}$$

in which the index 0 refers to the beginning of the period for which $\varepsilon_G$ was estimated. If the rate of decrease in storage capacity with time is a constant, so that d$S$/d$t$ = –$k$, then it results in equation (11), which describes the depletion of water availability within time for a given reliability level, as a function of $k$ (m$^3$ year$^{-1}$) and $\varepsilon_G$ (-):

$$Q_G(t + \Delta t) = Q_G(t) \cdot \left(1 - k \cdot \Delta t / S(t)\right)^{1/\varepsilon_G} \tag{11}$$

# RESULTS AND DISCUSSION

## Field survey

The long silting history of the reservoirs, ranging from 46 years for Várzea Boi and S. Mateus reservoirs to 94 years for the Cedro Reservoir, with an average of 68.5 years

(Table 2), allows for conclusions to be drawn at time scales which are relevant for water resources planning. Within these periods, the storage capacity of the reservoirs decreased by a 0.18% year$^{-1}$ for the rural watersheds and 0.56% year$^{-1}$ for the urban S. Anastácio Reservoir. The reduction in storage capacity usually implies a reduction in water availability, because the reservoirs will have less spare storage volume in the rainy season, leading to greater spillway overflows. The spillway discharge can be considered a loss in terms of the reservoir water availability, although not necessarily for the whole reservoir network, if its overflow reaches a more efficient reservoir (i.e. with a smaller value of $\overline{\alpha}$) downstream. The urban reservoir lost volume at a rate three times higher than the rural ones. The measured urban sediment contribution of the S. Anastácio watershed from 1992 to 2002 totalled 21 kg year$^{-1}$ *per capita*, a very high value caused by the rapid, non-regulated urbanization process of the catchment area (Araújo & Knight, 2005). In this watershed, the sanitation infrastructure standard is low (high sediment yield) and impervious surface is considerable (runoff of

**Table 2** Reservoir silting and water availability of the selected watersheds obtained by field survey and stochastic modelling. [a]

| | Várzea Boi | Cedro | Canabrava | Várzea Volta | S. Anastácio | S. Mateus | Acarape |
|---|---|---|---|---|---|---|---|
| Year of construction (initial year) | 1954 | 1906 | 1944 | 1919 | 1918 | 1954 | 1924 |
| Storage capacity $S_0$ (Mm$^3$) | 51.9 | 125.7 | 1.22 | 12.5 | 0.51 | 10.3 | 34.1 |
| Coefficient $\overline{\alpha}$ | 23464 | 33622 | 1067 | 11269 | 2963 | 2932 | 2115 |
| Yield $G$ = 99% (Mm$^3$ year$^{-1}$) | 4.33 | 0.74 | 0.026 | 1.12 | 0.190 | 0.92 | 8.11 |
| Yield $G$ = 90% (Mm$^3$ year$^{-1}$) | 10.32 | 5.67 | 0.090 | 2.66 | 0.317 | 2.09 | 11.88 |
| Yield $G$ = 80% (Mm$^3$ year$^{-1}$) | 14.16 | 9.04 | 0.120 | 3.67 | 0.390 | 2.99 | 13.82 |
| Yield $G$ = 70% (Mm$^3$ year$^{-1}$) | 16.62 | 12.17 | 0.150 | 4.39 | 0.450 | 3.50 | 15.46 |
| Year of control survey (final year) | 2000 | 2000 | 2000 | 2000 | 2002 | 2000 | 1997 |
| Storage capacity $S_0$ (Mm$^3$) | 46.1 | 105.1 | 1.13 | 11.0 | 0.27 | 8.9 | 31.4 |
| Coefficient $\overline{\alpha}$ | 47983 | 41220 | 1338 | 21172 | 3937 | 3965 | 2412 |
| Yield $G$ = 99% (Mm$^3$ year$^{-1}$) | 2.02 | 0.47 | 0.012 | 0.61 | 0.088 | 0.86 | 7.72 |
| Yield $G$ = 90% (Mm$^3$ year$^{-1}$) | 7.07 | 4.94 | 0.075 | 2.04 | 0.137 | 1.70 | 11.29 |
| Yield $G$ = 80% (Mm$^3$ year$^{-1}$) | 11.02 | 8.43 | 0.105 | 2.76 | 0.240 | 2.51 | 13.27 |
| Yield $G$ = 70% (Mm$^3$ year$^{-1}$) | 13.32 | 11.27 | 0.141 | 3.50 | 0.300 | 3.02 | 14.88 |
| Volume decrease $k/S_0$ (% year$^{-1}$) | 0.24 | 0.17 | 0.12 | 0.15 | 0.56 | 0.30 | 0.11 |
| Silting rate (t km$^{-2}$ year$^{-1}$) [B] | 124.3 | 1,276.6 | 701.8 | 160.9 | 460.9 | 188.9 | 231.8 |
| Yield ($G$ = 90%) decrease (% year$^{-1}$) | 0.68 | 0.14 | 0.30 | 0.29 | 0.68 | 0.41 | 0.07 |

[a] Water yields and respective reliability levels were modelled. All other data were measured.
[b] Reservoir sedimentation per unit catchment area per unit time.

410 mm year$^{-1}$ compared to an average of 90 mm year$^{-1}$ in the rural watersheds, see Table 1). On average, the reservoir silting rate reached 449 t km$^{-2}$ year$^{-1}$ (Table 2), where Várzea Boi Reservoir presented the minimum rate (124 t km$^{-2}$ year$^{-1}$), and Cedro Reservoir the maximum rate (1277 t km$^{-2}$ year$^{-1}$). The reason for such a high rate at Cedro is the combination of three aspects: (a) very steep slopes in the upper basin of the main river; (b) low environmental conservation status of the watershed (both augment soil erosion); and (c) the high average residence time of water within the reservoir (4.86 years, see Table 1), which enhances its trap efficiency for sediments. The reservoir-shape coefficient $\overline{\alpha}$ increased for all reservoirs during the observation periods, with an average rate of 0.77% year$^{-1}$. The increase in $\overline{\alpha}$ implies growing evaporation losses, which are already very high for the region: roughly 30% of the annual inflow (Campos, 1996).

## Water availability assessment

Water availability was assessed using the stochastic modelling approach for both reference years. Table 2 presents the water yield corresponding to the reliability levels 99, 90, 80 and 70% for the selected reservoirs, as well as evaporation and spillway discharges. In most of the analyses below, the 90% reliability level is used due to its broad application in water resources planning in the Brazilian semiarid region. The 90%-reliability yield ($Q_{90}$) decreased by 0.37% year$^{-1}$, on average, for all reservoirs and observation periods. Individual analyses indicated that the Várzea Boi Reservoir showed the most significant reduction in $Q_{90}$ (0.68% year$^{-1}$), whereas Acarape had the least (0.07% year$^{-1}$). The water availability curves for these reservoirs are presented in Fig. 3.

The impact on water availability can be accounted for from two perspectives: first, as a change in reliability for a predefined withdrawal volume, and, second, as a change in available withdrawal volume for a given reliability level. For Várzea Boi, for instance, 10.32 Mm$^3$ year$^{-1}$ could be taken with 90% reliability in 1954; but only 7.07 Mm$^3$ year$^{-1}$ could be withdrawn with the same reliability in 2000. This reduction in water availability corresponds to a considerable loss of water resources, which would be sufficient to irrigate about 540 ha of maize, assuming local water demand of 6000 m$^3$ ha$^{-1}$ year$^{-1}$. Considering the 99% reliability level, which is more adequate when referring to sustainable human supply, the difference in Várzea Boi yield between 1954 and 2000 was 2.31 Mm$^3$ year$^{-1}$, which corresponds to a decrease in the water supply for 42 000 people, under assumption of *per capita* consumption of 150 L day$^{-1}$. For the constant withdrawal rate of 10.32 Mm$^3$ year$^{-1}$, for example, the annual reliability level decreased from 90% to 81%, which means that the annual probability of water shortage rose from 10% to 19%. Even in the reservoirs with low siltation impacts, such as Acarape Reservoir (see, e.g. in Fig. 3(b), the high reliability level for withdrawal volumes up to about 6.0 Mm$^3$ year$^{-1}$ in both reference years), the reduction in water availability is noticeable. From 1924 to 1997, a reduction of 0.59 Mm$^3$ year$^{-1}$ was estimated for the 90% reliable water yield ($Q_{90}$), which would correspond to a cut-off of about 100 ha maize irrigation. The 99% reliability yield was reduced by 0.39 Mm$^3$ year$^{-1}$ during the study period, which is enough to supply over 7000 inhabitants. The reliability level, for an 11.88 Mm$^3$ year$^{-1}$ withdrawal, slightly decreased from 90% in 1924 to 88.5% in 1997. Table 3 presents water balance data from the stochastic simulations considering a reliability level of 90%.

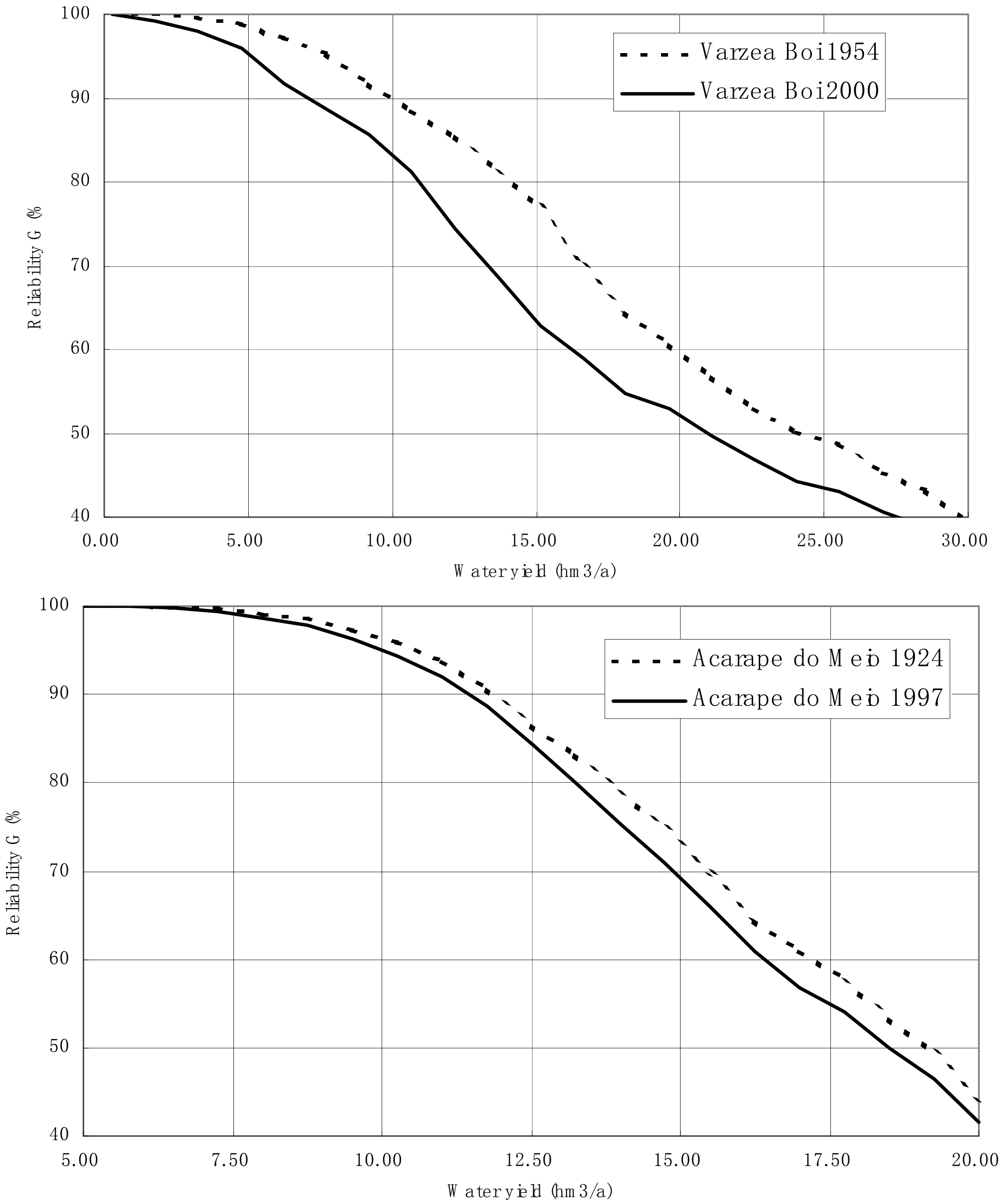


**Fig. 3** Simulated reliability level in two reservoirs as a function of water yield and time: (a) Várzea Boi, (b) Acarape.

The analysis for the initial situation indicated that, on average for all reservoirs, yield (i.e. the real withdrawal volume that could be provided for the operation rule explained above in 90% of the years) corresponded to 24% of annual inflow, whereas evaporation was 31% and spillway overflow 45% of annual inflow, respectively. For the final situation, after several decades of reservoir silting, yield share was reduced to 20%, evaporation rose to 32% and spillway overflow to 48% of annual inflow. On

**Table 3** Water balance for 90%-reliability yield ($Q_{90}$) in the selected reservoirs.

| | Várzea Boi | Cedro | Canabrava | Várzea Volta | S. Anastácio | S. Mateus | Acarape |
|---|---|---|---|---|---|---|---|
| *Initial situation* | | | | | | | |
| Average simulation inflow ($hm^3 a^{-1}$) | 46.12 | 26.49 | 0.320 | 12.42 | 3.159 | 12.22 | 19.84 |
| Average yield ($Q_{90}$) ($Mm^3 year^{-1}$) (24%) | 9.44 (20%) | 5.84 (22%) | 0.082 (26%) | 2.41 (19%) | 0.306 (10%) | 2.06 (17%) | 11.43 (57%) |
| Average evaporation ($Mm^3 year^{-1}$) (31%) | 11.01 (24%) | 16.96 (64%) | 0.215 (67%) | 2.81 (23%) | 0.159 (5%) | 1.82 (15%) | 3.51 (18%) |
| Average spillway discharge ($Mm^3 year^{-1}$) (45%) | 25.67 (56%) | 3.69 (14%) | 0.023 (7%) | 7.20 (58%) | 2.694 (85%) | 8.34 (68%) | 4.90 (25%) |
| *Final situation* | | | | | | | |
| Average simulation inflow ($Mm^3 year^{-1}$) | 45.22 | 26.82 | 0.319 | 12.56 | 3.191 | 12.35 | 19.94 |
| Average yield ($Q_{90}$) ($Mm^3 year^{-1}$) (20%) | 6.63 (15%) | 4.62 (17%) | 0.072 (23%) | 1.96 (16%) | 0.134 (4%) | 1.70 (14%) | 10.82 (54%) |
| Average evaporation ($Mm^3 year^{-1}$) (32%) | 12.69 (28%) | 17.10 (64%) | 0.220 (69%) | 3.08 (25%) | 0.117 (4%) | 1.82 (15%) | 3.55 (18%) |
| Average spillway discharge ($Mm^3 year^{-1}$) (48%) | 25.90 (57%) | 5.10 (19%) | 0.027 (8%) | 7.52 (59%) | 2.940 (92%) | 8.83 (71%) | 5.57 (28%) |
| Evaporation impact $\Delta Q_E$/abs($\Delta Q_{90}$) (+26%) | +88% | +9% | +56% | +46% | –21% | +1% | +5% |
| Overflow impact $\Delta Q_S$/abs($\Delta Q_{90}$) (+74%) | +12% | +91% | +44% | +54% | +121% | +99% | +95% |

average, the increase in evaporation from the reservoir was responsible for about 26% of yield reduction, whereas the increase in spillway losses explained 74% of the simulated reduction in reservoir yield (see the last two rows of Table 3). This means that water availability (yield) is more sensitive to the reduction in storage capacity in the course of reservoir siltation (higher volumes of water discharged through the spillway, so called spillway losses) than to the related morphological changes (higher evaporation losses). This relationship was observed in all reservoirs, except for Várzea Boi and Canabrava, where the change in morphology had a greater impact on water availability than volume reduction. For S. Mateus and Acarape reservoirs, on the other hand, the change in evaporation losses was very low, and water yield was reduced primarily by increase in spillway discharges. The urban reservoir of S. Anastácio was the only one in which the morphological change caused a reduction in average evaporation losses. A low initial residence time (0.16 years in 1918, see Table 1) and the marked reduction of reservoir storage capacity (from 0.51 to 0.27 $Mm^3$ in 84 years) led to a very high increment in spillway losses. It is important to note that higher spillway losses might have a positive impact on the system as a whole if a large, efficient reservoir is located downstream. Nonetheless, it represents less water available for the specific reservoir's users, as well as a negative pumping effect, i.e. water will be available at lower altitudes in the catchment.

## Yield–volume elasticity

Application of equation (10) to the watersheds for reliability levels of 99, 90, 80 and 70% allowed estimation of respective yield–volume elasticity, as shown in Table 4 and Fig. 4. The overall median elasticity was 0.793 (overall average 1.028), whilst average, median and minimum elasticity increased as the reliability level decreased. Thus, reservoir siltation tends to have a more severe impact on those reservoir yields that are to be provided with lower reliability. An exception is the S. Mateus Reservoir, which showed a strong increase of the elasticity for the 99% level when compared, for example, with the 90% level. Using time-average $\varepsilon_{90}$ and $k$ values for each reservoir in equation (11), the temporal evolution of water availability ($Q_{90}$) was simulated for a 50-year silting period (Fig. 5). The most critical reservoirs were S. Anastácio and Várzea Boi, with an expected reduction in $Q_{90}$ of 35%. For S. Anastácio Reservoir, the result is due to its high silting rate, which enhanced abruptly the spillway discharges.

**Table 4** Yield–volume elasticity (ε) as a function of reliability level (G) for the selected watersheds.

| Watershed (named after the outlet reservoir) | ε (99%) | ε (90%) | ε (80%) | ε (70%) |
|---|---|---|---|---|
| Várzea Boi | 0.155 | 0.313 | 0.473 | 0.535 |
| Cedro | 0.394 | 1.294 | 2.570 | 2.319 |
| Canabrava | 0.099 | 0.420 | 0.574 | 1.239 |
| Várzea Volta | 0.210 | 0.482 | 0.449 | 0.564 |
| S. Anastácio | 0.826 | 0.760 | 1.310 | 1.569 |
| S. Mateus | 2.151 | 0.745 | 0.885 | 1.020 |
| Acarape | 1.663 | 1.623 | 2.004 | 2.128 |
| Average | 0.786 | 0.805 | 1.180 | 1.339 |
| Standard deviation | 0.815 | 0.484 | 0.828 | 0.706 |
| Median | 0.394 | 0.745 | 0.885 | 1.239 |
| Minimum | 0.099 | 0.313 | 0.449 | 0.535 |
| Maximum | 2.151 | 1.623 | 2.570 | 2.319 |

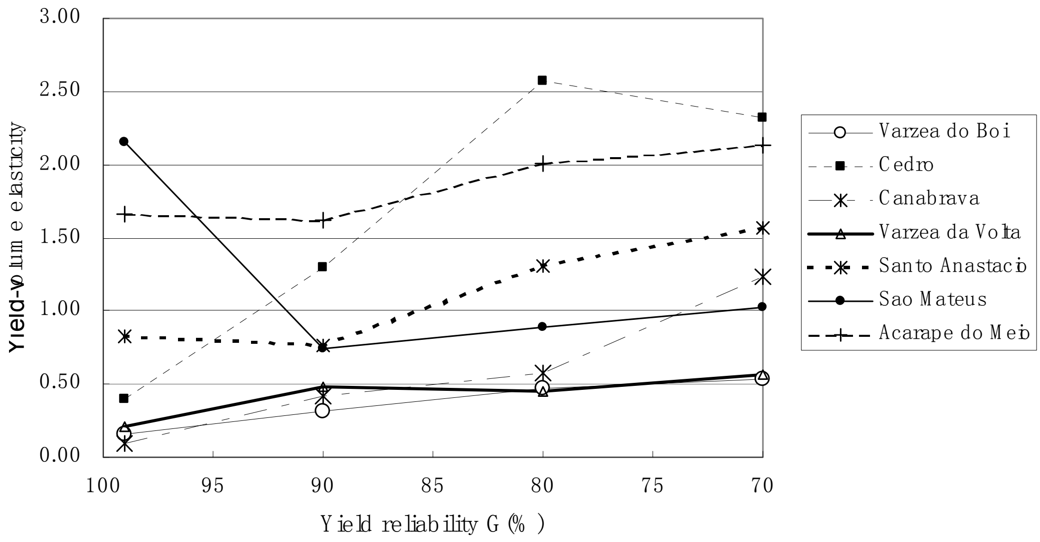


**Fig. 4** Yield–volume elasticity as a function of reliability level for the selected watersheds.

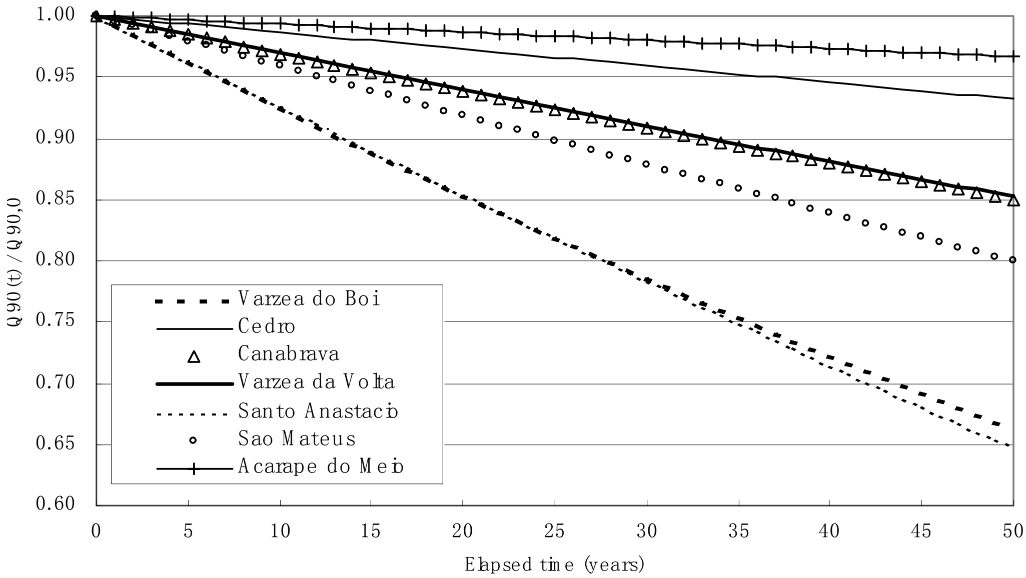


**Fig. 5** Simulation of the impact of reservoir sedimentation on water availability (rate of $Q_{90}(t)$ by $Q_{90}$ in the initial year) for the selected watersheds, for a 50-year period, admitting constant ε and *k*.

Várzea Boi Reservoir, on the other hand, suffered substantial increase of its shape coefficient ($\overline{\alpha}$), which led to much higher evaporation losses in spite of comparatively low silting rates (Table 2). The least critical reservoir is Acarape, which lost only about 3.5% of $Q_{90}$ in the simulation period. This is the result of good environmental conservation of the watershed associated with efficient morphology (very low $\overline{\alpha}$ in both reference years) and a well-dimensioned reservoir (mean residence time 1.2 years), as recommended for the Brazilian semiarid region (see Campos, 1996). Canabrava and Várzea Volta reservoirs behaved almost identically, with typical $Q_{90}$ reduction of 15% in 50 years. The Water Management Company of Ceará (COGERH) operates, together with the Federal Department DNOCS, the 123 largest reservoirs in the Ceará State. The total storage capacity of these reservoirs is approximately 17 570 Mm$^3$ and yield $Q_{90}$ totals 4170 Mm$^3$ year$^{-1}$ (COGERH, 2004). Applying the average volume reduction ($k/S_0$ = 0.236% year$^{-1}$, Table 2) and the average elasticity ($\overline{\varepsilon}_{90}$ = 0.805, Table 4) of the seven investigated reservoirs to the COGERH/DNOCS operated reservoirs, storage capacity is expected to decrease by 41 Mm$^3$ year$^{-1}$, and water yield with 90% reliability is expected to decrease yearly by 12.2 Mm$^3$ year$^{-1}$ (388 L s$^{-1}$) due to siltation.

## CONCLUSIONS

According to the results of the research, the main conclusions are: (a) reservoir silting has a relevant impact on water availability in the Brazilian semiarid region; (b) field surveys of seven basins showed average annual reservoir storage capacity reduction of 0.56% in an urban watershed and 0.18% in the rural ones due to siltation; (c) the average siltation rate reached 450 t km$^{-2}$ year$^{-1}$ and reservoir morphology changed towards a more open geometry, which favours evaporation losses; (d) simulations for the most critical reservoir showed that the probability of yearly water shortage almost doubled in less than five decades; (e) at the 90% reliability level, reduction in storage capacity had three times more impact on yield reduction than the increase in evaporation, although in two of the investigated watersheds, the morphological (evaporation) impact surpassed the volume reduction (overflow) impact; (f) the average yield–volume elasticity of the studied watersheds was 0.8 for 90% reliability level; (g) the elasticity increased with decreasing reliability level, which means that water uses, which are served with lower reliability, are more sensitive to reservoir silting than those with higher reliability; and (h) assuming the average parameters of the sample, storage capacity in Ceará should reduce by 41 $Mm^3$ yearly, and water yield ($Q_{90}$) should diminish by 388 L $s^{-1}$ every year. The present research accounted only for the quantitative impact of reservoir silting on water availability, although water quality impact of the sediments on water availability is also expected.

**Acknowledgements** The authors are grateful to the Brazilian Government (CAPES—*Fundação Coordenação de Aperfeiçoamento do Pessoal de Nível Superior*, process BEX 1540/03-3) for the post-doctorate scholarship granted to the first author, to the University of Birmingham and to Prof. Donald W. Knight, for their support.

## REFERENCES

Araújo, J. A. A. (1990) *Barragens do Nordeste do Brasil* (Dams in the Northeast of Brazil, in Portuguese). DNOCS – Departamento Nacional de Obras Contra as Secas, Fortaleza, Brazil.

Araújo, J. C. & Knight, D. W. (2005) 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* (ed. by R. Batalla), 126–131. IAHS Publ. 299, IAHS Press, Wallingford, UK

Araújo, J. C., Bronstert, A. & Güntner, A. (2005) Influence of reservoir sedimentation on water yield in the semiarid region of Brazil. In: *Sediment Budgets* (ed. by D. Walling & A. Horowitz), 301–307. IAHS Publ. 292, IAHS Press, Wallingford, UK.

Araújo, J. C., Fernandes, L., Machado, J. C., Jr, Oliveira, M. R. L. & Sousa, T. C. (2003) Sedimentation of reservoirs in semiarid Brazil. In: *Global Change and Regional Impacts* (ed. by T. Gaiser, M. Krol, H. Frischkorn & J. C. Araújo), 205–216. Springer-Verlag, Berlin, Germany.

Campos, J. N. B. (1996) *Dimensionamento de Reservatórios* (*Reservoir Design*, in Portuguese). UFC – Federal University of Ceará, Fortaleza, Brazil.

Campos, J. N. B., Araújo, J. C. & Sousa Filho, F. A. (1997) Errors and variability of reservoir yield estimation as a function of the coefficient of variation of annual inflows. In: *Managing Water: Coping with Scarcity and Abundance, Proceedings XXVII Congress of the IAHR* (ed. by Marshall English and Andras Szollosi-Nagy), 524–529. Am. Soc. Civil Engrs, New York, USA.

COGERH (2004) http://www.cogerh.com.br, 08/11/2004. Fortaleza, Brazil.

Departamento Nacional Meteorologia (1992) *Normais Climatológicas* (*Climate Normals*, in Portuguese). Brasília.

Fasching, R. A. & Bauder, J. W. (2001) Evaluation of agricultural sediment load reductions using vegetative filter strips of cool season grasses. *Water Environ. Res*. **73**(5), 590–596.

Gaiser, T., Krol, M., Frischkorn, H. & Araújo, J. C. (eds) (2003) *Global Change and Regional Impacts*. Springer Verlag, Berlin, Germany.

Güntner, A., Krol, M., Araújo, J. C. & Bronstert, A. (2004) Simple water balance modelling of surface reservoir systems in a large data-scarce semiarid region. *Hydrol. Sci. J.* **49(**5), 901–918.

Hantush, M. M. & Kalin, L. (2005) Uncertainty and sensitivity analysis of runoff and sediment yield in a small agricultural watershed with KINEROS2. *Hydrol. Sci. J.* **50**(6), 1151–1171.

Lane, L. J., Hermandez, M. & Nichols, M. (1997) Processes controlling sediment yield from watersheds as functions of spatial scales. *Environ. Modelling Software* **12**(4), 355–369.

Liénou, G., Mahé, G., Olivry, J.-C., Naah, E., Servat, E., Sigha-Nkamdjou, L., Sighomnou, D., Ngoupayou, J. N., Ekodeck, G. E. & Paturel, J. E. (2005) Régimes des flux des matières solides en suspension au Cameroun: revue et synthèse à l'échelle des principaux écosystèmes; diversité climatique et actions anthropiques. *Hydrol. Sci. J.* **50**(1), 111–123.

McMahon, T. A. & Mein, R. G. (1986) *River and Reservoir Yield*. Water Resources Publications, Littleton, Colorado, USA.

Morris, G. L. & Fan, J. (1997) *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use*. McGraw-Hill, New York, USA.

Nelson, E. J. & Booth, D. B. (2002) Sediment sources in an urbanizing, mixed land-use watershed. *J. Hydrol.* **264**, 51–68.

Oliveira, M. A. (1999) Eutrofização antrópica em reservatórios tropicais de pequena profundidade (Anthropogenic eutrophication of shallow tropical reservoirs, in Portuguese). Doctorate Dissertation, DEHA, UFC – Federal University of Ceará, Fortaleza, Brazil.

SRH (Secretaria de Recursos Hídricos) (1996) *Plano Diretor da Bacia do Curu* (*Strategic Plan for the Curu Basin*, in Portuguese) Fortaleza, Brazil.

SRH (Secretaria de Recursos Hídricos) (2000) *Plano de Gerenciamento das Águas da Bacia do Rio Jaguaribe* (*Water Management Plan for the Jaguaribe River Basin*, in Portuguese), vol. 1(II). Fortaleza, Brazil.

SRH (Secretaria de Recursos Hídricos) (2001) *Plano de Gerenciamento das Bacias Metropolitanas* (*Water Management Plan for the Metropolitan Basins*, in Portuguese), vol. 1(I). Fortaleza, Brazil.

Verstraeten, G. & Poesen, J. (2001) Variability of dry sediment bulk density between and within retention ponds and its impact on the calculation of sediment yields. *Earth Surf. Processes Landf.* **26**, 375–394.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209–237.

**Received 4 May 2005; accepted 17 October 2005**