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Sediment redistribution due to a dense reservoir network in a large semi-arid Brazilian basin

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Abstract This paper investigates for a 25-year period the sediment distribution in a semi-arid Brazilian basin ($2 \times 10^4 \text{ km}^2$) with a network containing more than 4000 surface reservoirs. The methodology is based on rating curves and fitted parameters derived from field data. The results showed that suspended load corresponded to 70% of the total sediment yield ($148 \text{ t km}^{-2} \text{ year}^{-1}$). The relatively low contribution of the suspended load (compared with other semi-arid regions) was attributed to the impact of the numerous upstream reservoirs, which retained $235 \text{ t km}^{-2} \text{ year}^{-1}$. The micro ($<1 \text{ hm}^3$), small ($1\text{--}10 \text{ hm}^3$), medium-sized ($10\text{--}50 \text{ hm}^3$), and large or strategic ($>50 \text{ hm}^3$) reservoirs responded to, respectively, 5, 17, 30 and 48% of the total sediment retention by the reservoir network. This indicates that retention in the non-strategic reservoirs has a positive impact on water availability, since siltation of the strategic reservoirs would be expected to more than double if only such reservoirs existed.

Key words reservoir network; siltation; sediment yield; semi-arid watershed; Brazil

Redistribution des sédiments due à un réseau dense de réservoirs dans un grand bassin versant semi-aride du Brésil

Résumé Cet article étudie sur une période de 25 ans la distribution des sédiments dans un bassin versant semi-aride du Brésil ($2 \times 10^4 \text{ km}^2$) qui est équipé d'un réseau de plus de 4000 réservoirs de surface. La méthodologie est basée sur les courbes de tarage et les paramètres ajustés provenant des données du terrain. Les résultats montrent que la charge en suspension correspond à 70% de la production totale de sédiments ($148 \text{ t km}^{-2} \text{ an}^{-1}$). La contribution relativement faible de la charge en suspension (par rapport aux autres régions semi-arides) est attribuée à l'impact des nombreux réservoirs en amont, qui retiennent $235 \text{ t km}^{-2} \text{ an}^{-1}$. Les réservoirs très petits ($<1 \text{ hm}^3$), petits ($1\text{--}10 \text{ hm}^3$), moyens ($10\text{--}50 \text{ hm}^3$), et grands ou stratégiques ($>50 \text{ hm}^3$) représentent, respectivement, 5, 17, 30 et 48% de la rétention totale de sédiments par le réseau de réservoirs. Cela indique que la rétention dans les réservoirs non-stratégiques a un impact positif sur la disponibilité de l'eau, puisque la sédimentation dans ces réservoirs stratégiques pourrait plus que doubler si eux seuls existaient.

Mots clefs réseau de réservoirs; sédimentation; production de sédiments; bassin versant semi-aride; Brésil

INTRODUCTION

The global trend of water demand has contributed to a massive increase in the number of small and medium-sized surface reservoirs in dryland areas since the last century (Pisaniello *et al.*, 2006; Callow & Smettem, 2009; Malveira *et al.*, 2011). These reservoirs now face siltation, which results in sediment redistribution in river basins and strongly influences water availability. Such problems are already taking place,

for example, in the highly populated Brazilian semi-arid region, where thousands of on-river reservoirs have been constructed in order to store water in the rainy periods to compensate the deficits during the dry season, and minimize conflicts among water uses and users (de Araújo *et al.*, 2006). This policy produced a High-density Reservoir Network (HdRN) in the region, a complex system to be managed. As an example, Fig. 1 shows the spatial distribution of more than 4000 dams in the Upper Jaguaribe Basin—UJB

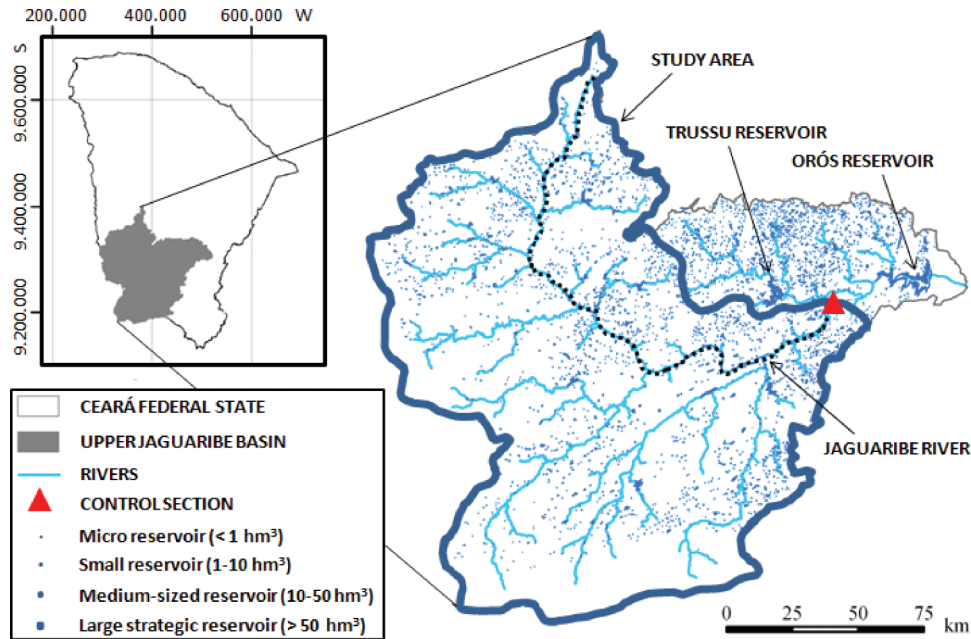


Fig. 1 Upper Jaguaribe Basin—UJB (24 600 km²) in the State of Ceará, Brazil, indicating the spatial distribution of almost 4100 reservoirs of different capacities; the Jaguaribe River; the control section; and the largest reservoirs of the basin (Orós and Trussu). The catchment area of the control section (20 700 km²) is shown within the UJB and contains approximately 3200 reservoirs.

(24 600 km²), in the Federal State of Ceará, Brazil. Since water uses and water conflicts are expected to increase globally, the problem of a HdRN may also occur in current non-drylands in the next decades. Therefore, it is of utmost importance to be able to assess reservoir siltation rates in HdRN basins, and their impact on the total sediment yield at the basin scale. This knowledge will help both to estimate the lifetime of reservoirs and to take proper measures against reservoir sedimentation and water scarcity. The investigated problem is also relevant in terms of geomorphology, considering that the existence of numerous reservoirs should change the natural patterns of sediment deposition.

The sediment yield at the basin scale has been defined as the amount of sediment transported beyond, or delivered to, a specific point in the catchment area per unit time (Morris *et al.*, 2008). Several investigations have presented empirical approaches relating sediment yield to catchment area, combined, or not, with other factors, such as basin shape, topography, runoff, lithology and vegetation cover (Walling, 1983; Church & Slaymaker, 1989; Verstraeten *et al.*, 2003; de Vente *et al.*, 2005; Minear & Kondolf, 2009). Others have presented distributed or semi-distributed hydro-sedimentological models such as WEPP (Flanagan *et al.*, 1995; Ramsankaram

et al., 2009), EUROSEM (Morgan *et al.*, 1998; Mati *et al.*, 2006), SWAT (Chen & Mackay, 2004; Rostamian *et al.*, 2008), HIDROSED (de Araújo & Knight, 2005; de Araújo, 2007), WATEM/SEDEM (Verstraeten *et al.*, 2007; de Vente *et al.*, 2008) and SEDNET (Prosser *et al.*, 2001; Wilkinson *et al.*, 2009), for the assessment of soil erosion and sediment yield at the basin scale. However, none of the above-mentioned empirical approaches and hydro-sedimentological models deals with the HdRN problem, as in the case of large basins of the Brazilian semi-arid region. In order to overcome this issue, Güntner & Bronstert (2004) developed the WASA—Model of Water Availability in Semi-arid Environments, one of the few hydrological models which is able to simulate such HdRN systems by dealing statistically with micro-, small and medium-sized dams. This model has been extended recently to a version called WASA-SED (Mamede, 2008; Francke *et al.*, 2008a) in order to include soil erosion and sediment dynamics modules. The WASA-SED has been applied to estimate the sediment distribution in two preserved, nested, semi-arid basins in Brazil with catchment areas of 12 and 933 km² (Medeiros *et al.*, 2010), respectively. However, the simulation and validation of that model for larger basins with a HdRN is a challenge that still needs to be tackled.

In this study, we present an alternative approach, based mainly on field data, to estimate the sediment yield and reservoir retention in relatively large basins with a HdRN. The case study is a watershed within the Upper Jaguaribe basin, a semi-arid catchment area of 20 700 km² (see Fig. 1). The temporal delimitation of the research is the 25-year period from 1984 to 2008. The reason for selecting this period is that, since the early 1980s, no major land-use change has been observed in the basin. The specific aims of this study are: (1) to generate a runoff time series using field data and hydrological modelling; (2) to generate a suspended sediment load time series using a rating curve obtained from field data; (3) to generate a bed load time series using a simple hydraulic model calibrated with field data; (4) to estimate the time variation of sediment deposition for different reservoir classes using field data and a relationship based on rainfall erosivity; and (5) to assess the total sediment production (reservoir retention plus sediment yield) at the basin scale. This study provides new data and a novel methodology that can be applied to predict the impact of numerous reservoirs on the sediment distribution in large basins.

STUDY AREA

General information

This study was conducted in a focus area of 20 700 km², corresponding to 84% of the total area of the UJB (see Fig. 1), located in the Federal State of Ceará, Brazil. The UJB population is approximately 500 000 inhabitants, living in 24 municipalities, whose economy is mainly cattle breeding and agriculture. One of the main constraints for the economic and social development of the area is the low water yield reliability, mainly due to recurrent droughts (whose probability of occurrence is close to 10%), a problem traditionally dealt with by the construction of local dams. The predominant vegetation type is *Caatinga*, a deciduous forest composed of a mixture of cacti, shrubs and trees not higher than 10 m. Frequently, the natural vegetation has been replaced by traditional agriculture (with predominance of maize and beans) and livestock farming. Intensive agricultural practices in the area have caused soil losses, as well as negative impacts on water quality (Aguiar *et al.*, 2006; Aquino *et al.*, 2008), which leads to less available water. Further information on the region can be found elsewhere (Aragão Araújo, 1990; Gaiser *et al.*, 2003).

Hydrology

The study area shown in Fig. 1 is within the drought polygon (Aragão Araújo, 1990), a tropical semi-arid region characterized by a strongly negative atmospheric water balance, comprised of: precipitation 700 mm year⁻¹ and potential evaporation above 2300 mm year⁻¹, with interception losses three times higher than runoff (Medeiros *et al.*, 2009); limited groundwater resources (fissured aquifers prevail); shallow soils on top of the crystalline basement; and recurrent droughts, leading to a highly vulnerable natural water resources system. According to Gaiser *et al.* (2003), rainfall in the study area is basically limited to a 4-month period (February–May), and about 70% of the total annual rainfall occurs within the rainy season.

River regime

The Jaguaribe River is the largest in the State of Ceará. Its catchment area is 74 000 km², corresponding to 50% of the State area. The peak flows in the river usually occur between March and April. At the UJB (Fig. 1), the river is intermittent, running dry for at least six months every year. Within the study area, the length of this river is about 300 km and its average slope is 0.60 m km⁻¹. At the control section, the total channel width between the outer banks is 180 m, while the regular water level rises up to 12 m. The highest flood stage at this section in the studied period (1984–2008) corresponded to a discharge of about 8000 m³ s⁻¹. Bed material in the main channel is primarily fine to coarse sand. The reason for choosing the control section shown in Fig. 1 was the availability of consistently measured water discharge since 1912. Despite the long-term monitoring of water discharge, sediment fluxes had only been assessed from isolated measurement campaigns conducted during the past decade, which shows the lack of information on sediment transport (and reservoir silting) in the UJB.

Surface reservoirs

Conflicts for water use in the Brazilian semi-arid region have occurred for centuries (Aragão Araújo, 1990), and governmental intervention has strongly relied on the construction of a reservoir network. Malveira *et al.* (2011) investigated the UJB and showed that, whereas in 1970 there were about 2200 dams in the basin, in 2002 there were almost 4100. The Orós Reservoir (with a storage capacity of

2000 hm³, constructed in 1961) is the largest of the UJB, and the Trussu Reservoir (300 hm³, constructed in 1996) is the second largest. In the catchment area of the control section inserted in the UJB (Fig. 1), we estimated a total of 3200 dams in 2002. This means that presently the density of micro (storage capacity below 1 hm³, hereafter referred to as C_I), small (capacity between 1 and 10 hm³, referred to as C_{II}) and medium-sized (capacity between 10 and 50 hm³, referred to as C_{III}) reservoirs is so high that the average direct catchment area is of the order of 6 km² (this is about 50 times smaller than the area–reservoir ratio reported by Minear & Kondolf, 2009, for the region of California, USA, for example). Among the 3200 dams, only five are considered strategic (capacity larger than 50 hm³, referred to as C_{IV}), i.e. those which can supply water throughout long-term (2–4 years) droughts. This includes the following reservoirs: Várzea do Boi (52 hm³, constructed in 1954), Poço da Pedra (52 hm³, 1958), Canoas (69 hm³, 1999), Muquém (50 hm³, 2000), and Arneiroz II (197 hm³, 2004).

METHODOLOGY

The methodology proposed here is based on rating curves and fitted parameters derived from field data to predict the impact of the HdRN on the sediment distribution (sediment retention at each reservoir class, and suspended sediment load and bed load at the control section) in the study area (see Fig. 1). In the following sub-sections: Rainfall and water discharge, Suspended sediment load, Bed load, and Reservoir sedimentation, we describe, respectively, how the time series of runoff, suspended sediment load, bed load, and sediment deposition for different reservoir classes were obtained. The subsequent sub-section Sediment balance describes how the total sediment production (reservoir retention plus sediment yield) is integrated for the catchment area of the control section, and also extrapolated for the whole UJB. Limitations and uncertainties of the methodology are also discussed in the last item of this section.

Rainfall and water discharge

Daily precipitation data for the period of 25 years (1984–2008) were obtained from 16 raingauges distributed in different municipalities within the study area. Consistency analysis was carried out based on the data of three continuous-measurement climate

stations. Water level, H (m), and discharge, Q (m³ s⁻¹; estimated from the rating curve $Q = 1.31H^{3.99}$; $r^2 = 0.97$) at the study control section were also obtained for the same period. Water level measurements were also taken on a daily basis, but during extreme events, hourly data were collected. The Geological Survey of Brazil (CPRM) verified the rating curve at least once per year for high discharges since 1999. These data were collected from the Hidroweb Database (Brazilian National Water Agency, ANA). In order to fill the missing discharge data (13% of the period, related to the total non-null data) in the 25-year series, we adopted two procedures: (a) for part of the rainy season of 2004 (year of extreme events, 1.5% of the non-null data), we subdivided the study area into four isochrones and used the modified Clark method (Kull & Feldman, 1998) to estimate the daily discharges; and (b) for the other periods (mostly dry season with very low discharges, 11.5% of the non-null data) we filled the series with the average discharge of the respective day based on the monitored years. This allowed us to generate a water discharge time series for the period of 25 years. The precipitation data were also used to estimate the rainfall erosivity corresponding to each rain gauge, which was later used to calculate reservoir sedimentation.

Suspended sediment load

Eight field surveys were conducted during the rainy season of 2008 to measure water discharge and suspended sediment load at the Jaguaribe River control section (see Fig. 1). Water velocity was measured across this section (20–22 verticals) using a propeller current meter equipped with a pulse meter, which was used to calculate the total water discharge. Suspended sediment samples were collected using a US DH-48 sampler (10–12 verticals). The samples were then taken to the laboratory for estimation of the suspended sediment concentration. The method used was that described by Diplas *et al.* (2008). Using the above-mentioned data combined with water discharge and suspended sediment concentration measurements from 1999 to 2009 provided by CPRM, we obtained total water discharges ranging from 1 to 500 m³ s⁻¹ and suspended sediment concentrations ranging from 30 to 600 mg L⁻¹, leading to loads ranging from 0.05 to 300 kg s⁻¹. Thus, considering all data points (our data plus the CPRM data), the following power-law rating curve was obtained:

$$Q_s = aQ^b \quad (1)$$

where Q_s is the suspended sediment load (kg s^{-1}), and a and b are parameters obtained by fitting the equation to the field data. Although hysteretic behaviours have been observed for water discharge–suspended sediment load relationships during floods (Vericat & Batalla, 2006; Megnounif *et al.*, 2007; Francke *et al.*, 2008b), they were neglected here. This is supported by previous studies in semi-arid regions, where approximately 90% of the flood events analysed did not present any hysteresis (Achite & Ouillon, 2007). A recent study conducted by Cherif *et al.* (2009) in a semi-arid basin in Algeria also showed that coefficients of determination higher than about 0.8 can be obtained by fitting equation (1) to field data. Therefore, we assumed that this equation type was sufficient to represent the variations in the suspended sediment load as a function of the water discharge. We also used additional data available in the literature to confirm the ability of equation (1) to predict the suspended sediment load for higher flow conditions (similar to the peak flows in the Jaguaribe River control section). This gave credence to equation (1) and allowed us to generate a daily suspended sediment load time series for the 25-year period.

Bed load

Four field surveys were conducted during the rainy season of 2009 in order to measure the bed load at the control section (Fig. 1). In the occasion, the water discharge was relatively low ($1\text{--}5 \text{ m}^3 \text{ s}^{-1}$). The bed material was collected using a US BLH-84 sampler for 10–12 verticals. The sediment samples were then taken to the laboratory for grain-size analysis (diameters ranging from about 3×10^{-4} to 3×10^{-2} m) and estimation of the bed load transport rate (ranging from about 0.05 to 0.20 kg s^{-1}), according to the method described by Diplas *et al.* (2008). We calibrated the energy line slope at the control section by introducing the above-mentioned data into a recently modified version of the Meyer-Peter and Müller bed load equation (Wong & Parker, 2006; García, 2008):

$$q^* = 3.97(\tau^* - 0.0495)^{3/2} \quad (2)$$

where q^* is the dimensionless bed load transport rate given by $q^* = q_b / (D\sqrt{gD\lambda})$; τ^* is the dimensionless shear stress, given by $\tau^* = HS / (D\lambda)$; q_b is the volumetric bed load transport rate per unit width ($\text{m}^2 \text{ s}^{-1}$); S is the energy line slope of the channel; D is a characteristic sediment diameter (m) (usually taken as D_{50} ,

the grain size for which 50% of the bed material is finer); λ is the submerged specific gravity of the sediment given by $\lambda = (\rho_s / \rho) - 1$; ρ_s is the density of the sediment; and ρ is the density of the water. This equation is expected to be applicable to the present study since the range of sediment diameters for which it was developed (3.4×10^{-4} to 3.0×10^{-2} m) is the same as that obtained from our field surveys. Here, D_{50} was equal to 8.5×10^{-4} m and this value was used in the simulations. We also used additional data available in the literature to confirm the ability of equation (2) to predict the bed load for higher flow conditions. This gave credence to equation (2) and allowed us to generate a daily bed load time series for the period of 25 years.

Reservoir sedimentation

Imagery of 1970 and 2002 was analysed, leading to the identification in the study area of about 1700 and 3200 reservoirs, respectively. These images, which were selected due to their high quality and temporal distance, were taken in the first months of the dry season (July–August), when the reservoirs were full (as verified with field measurements) and land surface visible. In order to assess the reservoir volume, V_o , the Molle (1991) empirical relationship, based on measurements of more than 400 small dams in the Brazilian semi-arid region, was used:

$$V_o = \frac{Ah}{\alpha} \quad (3)$$

where A is the inundated area (m^2) and h is the reference water height (m), which are related using the parameters α and β by the expression $h = \alpha^{-1} \sqrt{A / (\alpha \cdot \beta)}$. Average values of $\alpha = 2.7$ and $\beta = 1500$ were used in the present study (Molle, 1991). Thus, we could estimate the temporal evolution of reservoirs (and their volumes) per class from 1970 to 2008 as follows:

- (a) for the thousands of reservoirs of classes C_I , C_{II} and C_{III} , annual increment rates were assumed equal to those of the reservoirs monitored by the Federal and State water authorities in Ceará (Malveira *et al.*, 2011). We also assumed that the percentage of reservoirs for each of these three classes was constant throughout the period. This extrapolation fitted well the reservoirs observed in the satellite image of 2002. Such a procedure was conducted since most of these reservoirs

- remain unregistered because of the unofficial and/or unplanned aspect of their construction;
- (b) for the reservoirs of class C_{IV}, which had been registered by water authorities, simple counting was done. These larger reservoirs could also be easily visualized in the satellite images.

In order to assess the reservoir sedimentation rate, we proposed the (temporal mean) rate of sediment retention, ξ_m (t m⁻³ MJ⁻¹ mm⁻¹ ha h) as a key parameter:

$$\xi_m = \frac{\Delta V}{V_o} \frac{\rho}{\sum R} \quad (4)$$

where ΔV is the reservoir capacity reduction (hm³), ρ is the dry-bulk density of sediment (t m⁻³), and $\sum R$ is the cumulative rainfall erosivity factor (MJ mm ha⁻¹ h⁻¹). Note that the rainfall erosivity is one of the factors included in the universal soil loss equation (USLE), given by Wischmeier & Smith (1978). In this study, due to the lack of detailed data for the computation of 30-min rainfall intensity representative for the whole catchment, erosivity was obtained using equation (5a,b). This was proposed by Bertoni & Lombardi Neto (1990) for the southern region of Brazil, but verified as valid for the Brazilian semi-arid region too (de Araújo *et al.*, 2003):

$$R_m = 67.355 \left(\frac{P_m^2}{P} \right)^{0.85} \quad (5a)$$

$$R = \sum_{m=1}^{12} R_m \quad (5b)$$

where R_m and R are, respectively, the monthly and annual erosivity factors (MJ mm ha⁻¹ h⁻¹), and P_m and P are, respectively, the monthly total rainfall and the annual average rainfall (mm).

Measurements of V_o and ΔV obtained from surveys conducted in seven reservoirs ranging from class C_I to C_{IV} (de Araújo *et al.*, 2003) allowed us to calculate the rate of sediment retention ξ_m by using equation (4). The surveys were carried out at the end of the dry season so that the reservoir level was the lowest possible. Topographic surveys were conducted in the dry area, with density varying from 8 to 25 points per hectare. Bathymetric surveys were conducted in the wet area, with density varying from 5 to 60 points per hectare. In both cases, the smaller the reservoir, the higher the density of measurement points. Therefore, using an average value of the rate

of sediment retention ($\overline{\xi_m}$), we could estimate the sedimentation rate: (i) for classes C_I, C_{II} and C_{III}, whose reservoirs are randomly distributed in the study area, a spatial average value of the yearly erosivity factor (\overline{R}) was obtained, and equation (6) could be applied to estimate the total sediment retention per reservoir class per year; and (ii) for class C_{IV}, an annual erosivity factor obtained for the catchment area of the j th reservoir (R_j) was used; hence, we could apply equation (7) to estimate the total sediment retention per reservoir for every simulation year:

$$\Delta M_c = n_c V_{o,c} \overline{\xi_m} \overline{R} \quad (6)$$

$$\Delta M_j = V_{o,j} \overline{\xi_m} R_j \quad (7)$$

where ΔM_c is the total mass of sediment retention in the reservoir class (Mt), n_c is the number of reservoirs for class c , and $V_{o,c}$ is the class average initial volume of the reservoirs (hm). Note that: the number of reservoirs n_c increased in time with a yearly step; $V_{o,c}$ was fixed for each class; $\overline{\xi_m}$ is unique; and the erosivity factor \overline{R} varied on a yearly basis. In equation (7) ΔM_j is the total mass of sediment retention in the j th reservoir (Mt). Thus, the total sediment retention for class C_{IV} was the sum of ΔM_j for the five reservoirs located in the study area (Várzea do Boi, Poço da Pedra, Canoas, Muquém and Arneiroz II). Note that these reservoirs were constructed in different years. Volume $V_{o,j}$ was known for the j th reservoir, and erosivity factor R_j varied on a yearly basis. This procedure allowed us to generate a yearly sediment retention time series for each reservoir class for the period of 25 years. It should be noted that we also compared our average value of $\overline{\xi_m}$ to the values obtained from Medeiros (2009), Lima (2010), and the Water Resources Management Company of Ceará—COGERH (2010) (including 12 reservoirs distributed in the UJB and other basins within the State of Ceará) in order to validate the method described above.

Sediment balance

The sediment balance for 1984–2008 in the study area was obtained from the integration of the time series of total sediment load (suspended load plus bed load) at the control section, as well as reservoir sedimentation for each class (C_I to C_{IV}). The same methodology was also extrapolated to the whole UJB, including the effects of sediment retention in the reservoirs located

outside the study area, which correspond to approximately a quarter of the reservoirs of the UJB (see Fig. 1). Thus, the retention in the reservoirs of classes C_I, C_{II} and C_{III} was calculated using equation (6), while that in the class C_{IV} reservoirs (Trussu and Orós) was calculated using equation (7). The retention in the Orós Reservoir (the largest of the UJB) was also compared to the retention estimated from measurements, using the following equation:

$$\Delta M_{\text{Orós}} = (\Delta M_{\text{SL}} + \Delta M_{\text{BL}}) \delta T_E \quad (8)$$

where ΔM_{SL} and ΔM_{BL} are, respectively, the suspended load and bed load inflow at the control section upstream the Orós Reservoir (Mt), δ is the UJB area divided by the study area (to account for the additional sediment production in the whole basin), and T_E is the reservoir trap efficiency obtained from Brune's relationship (see Brune, 1953; García, 2008). It should be noted that the retention in the Orós, using equation (8), is based on the assumption that erosion and deposition processes in the reach of the Jaguaribe River between the control section and the reservoir entrance are in balance. This assumption is supported by the fact that no significant meandering pattern has been observed from aerial images in this river reach. The comparison above was important to validate our methodology based on equation (4) to assess reservoir sedimentation.

Limitations and uncertainties

Many parameters affect sediment distribution in large semi-arid basins with a HdRN, including: rainfall, water discharge, sediment characteristics, number of reservoirs, and catchment area/reservoir size and shape, which vary both spatially and temporally. The major limitations of our approach are: existence of a relatively small number of raingauges in the UJB; short-term monitoring of sediment fluxes; lack of data for extreme flood events in the control section; and availability of sedimentation data only for a few reservoirs. To complete the lacking data, we also used modelling and curve fitting, which involved calibration processes and uncertainties. Moreover, the methodology proposed here assumes that similar erosion, transport and deposition processes occur within the basin and throughout the study period. Therefore, our methodology is expected to predict regional trends of sediment distribution in the basin, but not accurate estimates of deposition within individual reservoirs. Caution should also be taken when

applying the methodology to other basins, since it is based on the assumptions of randomly distributed reservoirs (classes C_I–C_{III}) and no significant land-use change over the study period.

RESULTS AND DISCUSSION

Rainfall, water discharge and river sediment transport

Figure 2 shows the time series of average precipitation in the study area, as well as water discharge, suspended sediment load and bed load at the control section, obtained as described in the methodology above. In Fig. 2(a) and (b), it can be seen that the precipitation events, and their response as water discharge, occurred consistently during the rainy season (first six months of the year). However, rainfall was unusually high in 2004. The average daily precipitation in that period (5.6 mm) was about 50% higher than the 25-year average daily value for the same months (3.8 mm). This resulted in a peak water discharge of 8000 m³ s⁻¹ (about 7.0 × 10⁸ m³ d⁻¹), occurring in the middle of March 2004. It is interesting to note that the cumulative water discharge for January–June 2004 corresponded to about two thirds of the total cumulative value for the 25-year period.

Figure 2(c) shows the time series of suspended sediment load at the control section, obtained by using the rating curve shown in Fig. 3. This rating curve was generated by fitting equation (1) to the field data measured in 2008 and by the Geological Survey of Brazil (CPRM) from 1999 to 2009 ($r^2 = 0.91$, $n = 46$). It is interesting to observe that the data from both sources collapse well into the fitted curve, suggesting that no significant changes in the water discharge–suspended sediment relationship occurred during the study period (1984–2008). This probably occurred because the direct catchment area remained constant during low-flow conditions, whereas in high level of flooding events the small reservoirs played secondary roles, allowing a large amount of the sediment inflow to reach the reservoir spillway in such periods of high connectivity. Since our data and the CPRM data follow fairly similar trends, the results of using all data points or parts of them (as described in Horowitz, 2003) produced differences smaller than 20%. Therefore, our rating curve is expected to be consistent. The extrapolated point in Fig. 3 corresponds to the highest water discharge condition shown in Fig. 2(b) applying the curve given by Xu (2002), in which the saturated

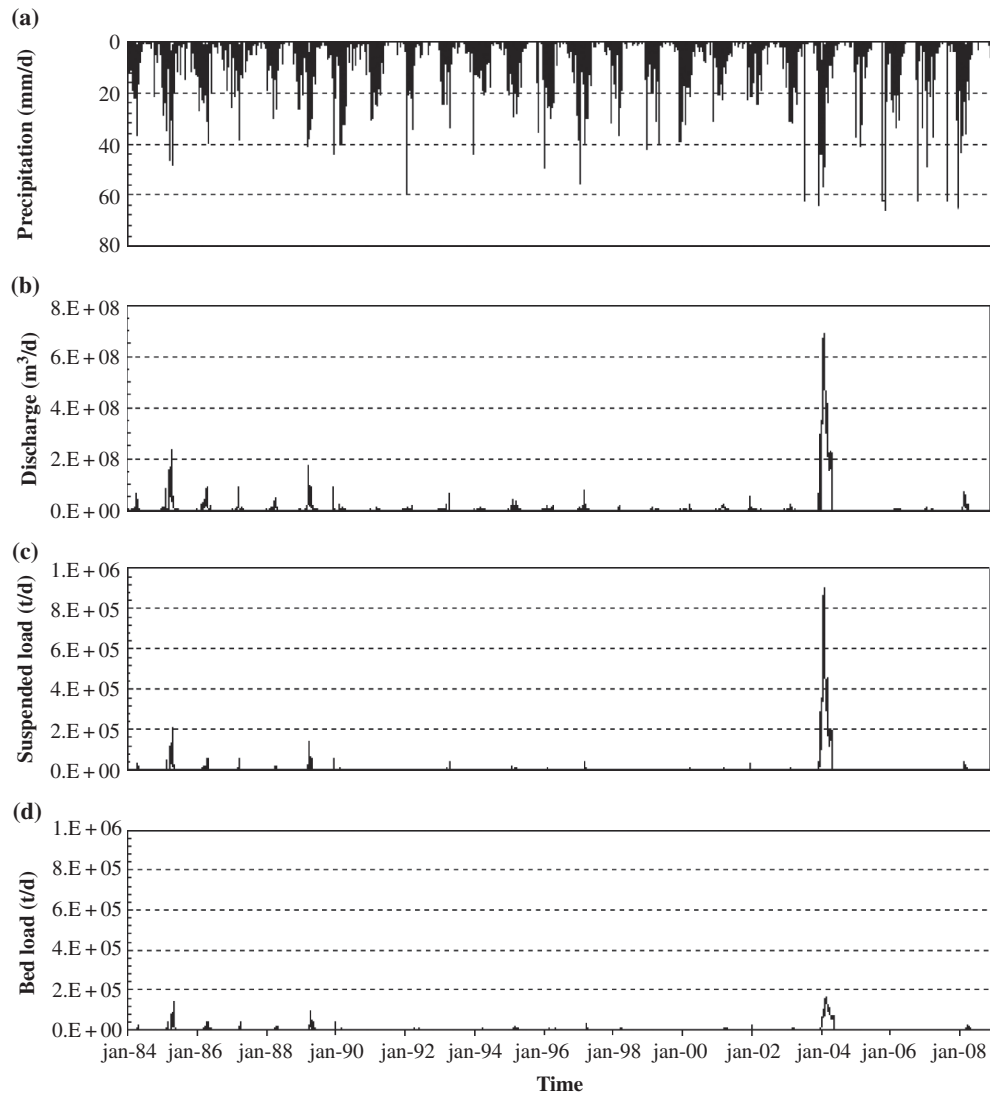


Fig. 2 Time series of: (a) average precipitation in the study area, (b) water discharge, (c) suspended sediment load, and (d) bed load at the Jaguaripe River control section.

suspended sediment concentration, C_s (mg L^{-1}) is a function of a dimensionless flow strength index, $\psi = v^3/(gwH)$, where g is the gravity acceleration, and v and w are the water flow velocity and the settling velocity of the sediment, respectively. Note that we used the straight-line portion of Xu's curve, which is based on data from a variety of rivers, irrigation channels and laboratory flumes at normal sediment concentrations, instead of the upper limb of the curve, which is based on hyperconcentrated flow regime data from Chinese rivers. Here we estimated $\psi = 22$ and $C_s = 850 \text{ mg L}^{-1}$ ($v = 4.4 \text{ m s}^{-1}$, $w = 0.04 \text{ m s}^{-1}$, and $H = 10 \text{ m}$), yielding a suspended sediment load Q_s of $588\,000 \text{ t d}^{-1}$, which is 30% lower than the value of $770\,000 \text{ t d}^{-1}$ obtained by extrapolating the rating curve (see Fig. 3). Considering that the

extrapolated point was not used for the curve fitting, it can be assumed that the rating curve predicts well the suspended sediment load expected for the highest discharge conditions. Similarly to the water discharge behaviour (see Fig. 2(b)), the major contribution of the suspended load occurred from January to June 2004 (see Fig. 2(c)), corresponding to approximately 83% of the total cumulative value for the 25-year period. The average yearly suspended load divided by the study area resulted in a specific suspended sediment yield of $102 \text{ t km}^{-2} \text{ year}^{-1}$, which ranges from about 10 to 75% of the values obtained in other semi-arid watersheds (Probst & Amiotte-Suchet, 1992; Megnounif *et al.*, 2003; Achite & Ouillon, 2007; Melo *et al.*, 2009). Another comparison can be made between the rating curve obtained in

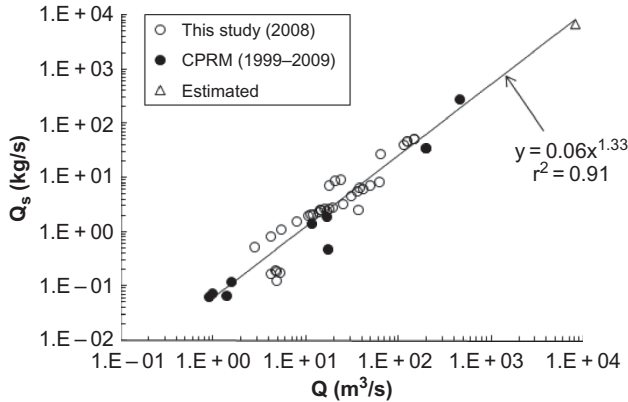


Fig. 3 Rating curve relating water discharge to suspended sediment load at the control section, obtained by fitting equation (1) to field data measured in the present study and by CPRM. The extrapolated point was estimated by applying the saturated suspended sediment concentration.

the present study ($Q_s = 0.06Q^{1.33}$) and that obtained by Cherif *et al.* (2009) in a semi-arid basin in Algeria ($Q_s = 5.72Q^{1.31}$). Although the two curves follow similar power laws, our suspended loads were about 100 times smaller (for the same water discharges). This lower suspended load is possibly a consequence of sediment retention in the numerous reservoirs in our study area, suggesting that most of the sediment transported downstream from the dams was due to reservoir overflow. Moreover, flood attenuation due to the existence of the dams might also have played an important role in reducing the ability of the flow to suspend and transport the sediments.

Figure 2(d) shows the time series of bed load at the Jaguaribe River control section obtained by equation (2), considering a calibrated energy line of slope $S = 0.75 \text{ m km}^{-1}$. We also evaluated other bed load equations available in the literature, such as those of Cheng, Bagnold, Brown, Einstein, Meyer-Peter & Müller, and Van Rijn (cited in García, 2008), but equation (2) presented the best fit to the field data (efficiency coefficient of 0.813, as defined by Nash & Sutcliffe, 1970), as well as a value of S close to the river slope (0.60 m km^{-1}). The comparison between measured and computed bed load transport rate is depicted in Fig. 4. The extrapolated point corresponds to the data measured by Gaeuman & Jacobson (2007) in a reach of the Missouri River, USA, with characteristics ($Q = 5500 \text{ m}^3 \text{ s}^{-1}$, $W = 200 \text{ m}$, $H = 9 \text{ m}$, $S = 0.16 \text{ m km}^{-1}$, and $D_{50} = 5.5 \times 10^{-4} \text{ m}$) similar to those in the studied reach of the Jaguaribe River. It can be seen that, for such conditions, equation (2) estimates a bed load per unit width of $1.6 \text{ kg s}^{-1} \text{ m}^{-1}$, which is only

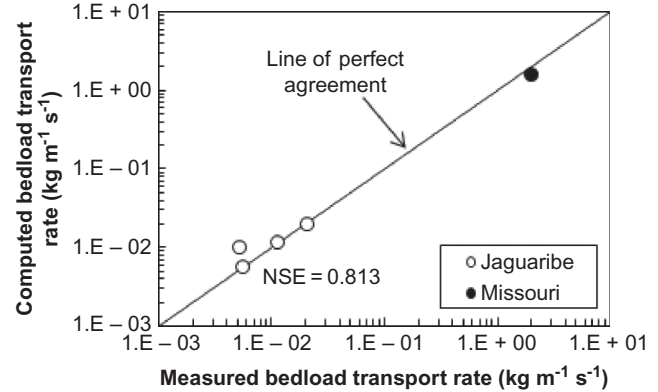


Fig. 4 Comparison between bed load transport rate measured in the control section and computed values using equation (2). The efficiency coefficient NSE is also indicated. The extrapolated point corresponds to the data measured by Gaeuman & Jacobson (2007).

20% lower than the value of $2.0 \text{ kg s}^{-1} \text{ m}^{-1}$ reported by Gaeuman & Jacobson (2007). This indicates that equation (2) predicted well the bed load for higher discharge conditions. The simulation using equation (2) for the 25-year period resulted in a maximum bed load of $163\,000 \text{ t d}^{-1}$ (see Fig. 2(d)). Similarly to the water discharge and suspended load behaviours (Fig. 2(b) and (c)), the major contribution of the bed load occurred between January and June 2004 (Fig. 2(d)), corresponding to approximately 50% of the total cumulative value for the 25-year period. The average bed load resulted in $46 \text{ t km}^{-2} \text{ year}^{-1}$, about 30% of the total river sediment load at the control section. This percentage is about 5-fold larger than values reported in semi-arid basins (Alexandrov *et al.*, 2009). A value of the same order of magnitude (40%) was also obtained by Vericat & Batalla (2006) in river reaches downstream from dams. However, in their case, the sediment diameter was larger ($D_{50} = 3 \times 10^{-2} \text{ m}$). The relatively high bed load percentage (or low suspended load percentage) reported here is probably due to reservoir sedimentation and flood attenuation, as mentioned above.

Reservoir sedimentation and sediment balance

The temporal evolution of reservoirs per class in the study area, obtained as described in the methodology above, is shown in Fig. 5. It can be seen that the number of reservoirs is inversely dependent on their class capacity. For example, in 2008, the number of reservoirs of class C_I was about 3100 while that of class C_{IV} was five. However, for the 25-year period (1984–2008), the number of reservoirs of class C_{IV} increased

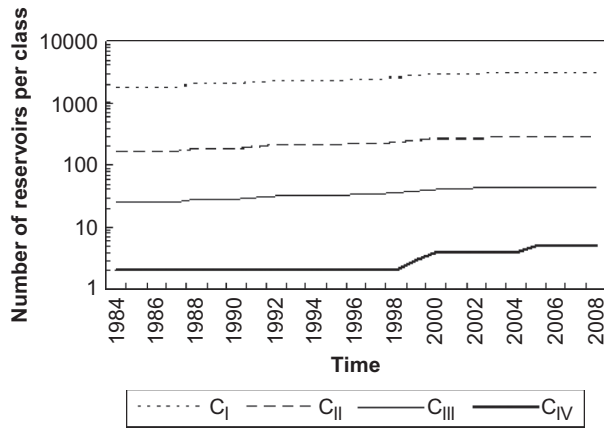


Fig. 5 Temporal evolution of micro (class C_I , $<1 \text{ hm}^3$), small (class C_{II} , $1\text{--}10 \text{ hm}^3$), medium-sized (class C_{III} , $10\text{--}50 \text{ hm}^3$) and large reservoirs (class C_{IV} , $>50 \text{ hm}^3$) in the study area.

about 4% per annum, while that of classes C_I , C_{II} or C_{III} increased only about 2% per annum. Similar increases in the number of reservoirs in dryland areas have also been reported by Pisaniello *et al.* (2006) and Callow & Smettem (2009).

Figure 6 shows the values of the rate of sediment retention, ξ_m , as a function of the initial storage capacity of the reservoirs, V_o . It is interesting to observe that ξ_m does not vary significantly with V_o and does not present any trend. Our average value ($\bar{\xi}_m$) corresponds to the data given by de Araújo *et al.* (2003), while the global average value also includes the data from Medeiros (2009), Lima (2010) and COGERH (2010) in order to validate the method. Note that Fig. 6 includes the results for 19 reservoirs of different locations (including the UJB and

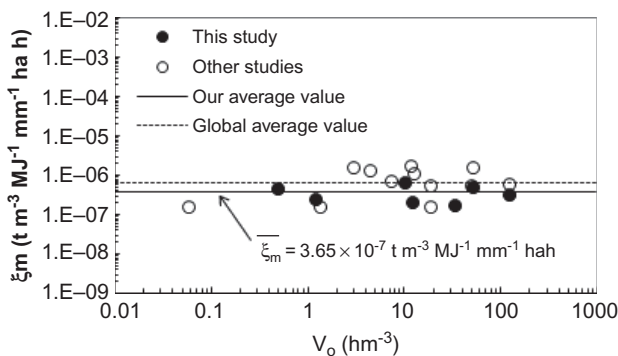


Fig. 6 Rate of sediment retention calculated from field measurements (de Araújo *et al.*, 2003) as a function of the initial storage capacity of the reservoirs (coefficient of variation is 0.49 without any trend). The global average value also includes data from Medeiros (2009), Lima (2010), and COGERH (2010).

other basins located in the State of Ceará), initial storage capacities (ranging from 0.06 to 126 hm^3), and operation periods (ranging from 6 to 103 years). Since reservoir sedimentation rate can also be estimated by the global product of $USLE \times SDR \times T_E$, where SDR is the sediment delivery ratio (see de Araújo *et al.*, 2003), it can be inferred that the parameter ξ_m becomes approximately constant for different reservoir classes if there is a balance among the global product of these three factors. A recent study conducted by Lima (2010) in a micro-reservoir in the UJB has showed that T_E can be as low as 7% (i.e. about six times lower than that predicted using Brune's relationship). In contrast to the larger reservoirs, the micro reservoirs in the semi-arid Brazilian region are usually designed to be filled every year (and also overflow water and sediment). A study conducted by Almeida (2001) in a medium sized-reservoir located in the State of Ceará has showed that T_E is about 86%, which is slightly lower than that predicted by using Brune's relationship. Therefore, while in smaller reservoirs $USLE \times SDR$ is expected to be high (i.e. there is a higher variability of rainfall erosivity, as well as a higher sediment yield), and T_E is expected to be low (i.e. there is a higher overflow of water and sediments), in larger reservoirs, the opposite is expected to occur. Note that the procedure for reservoir sizing (i.e. the determination of V_o , which is included in equation (4)) used in the State of Ceará usually takes into account the variability of some factors, such as catchment area, slope, and cover type (see Carvalho, 1983; Campos, 1996), which also have some impact on the USLE factors. Therefore, Fig. 6 suggests that equation (4) incorporates the variability of the global product of $USLE \times SDR \times T_E$ and can be used to estimate (at least as a first approximation) reservoir silting in large semi-arid Brazilian basins.

The average value of the rate of sediment retention ($\bar{\xi}_m = 3.65 \times 10^{-7} \text{ t m}^{-3} \text{ MJ}^{-1} \text{ mm}^{-1} \text{ ha h}$) obtained from Fig. 6 was used in equations (6) and (7) to estimate the sedimentation rate for the four reservoir classes in the study area. Figure 7 shows time series of this sedimentation rate, as well as a time series of the sediment yield (total sediment discharge, i.e. suspended load plus bed load; Fig. 2(c) and (d)) at the Jaguaribe River control section. It may be observed that the two sets of curves in Fig. 7 present some degree of correlation ($r = 0.40$), regardless of the fact that they have been constructed independently from each other, using different methods. An evaluation of these curves over the 25-year period resulted in sediment retention by reservoirs of 122 Mt or

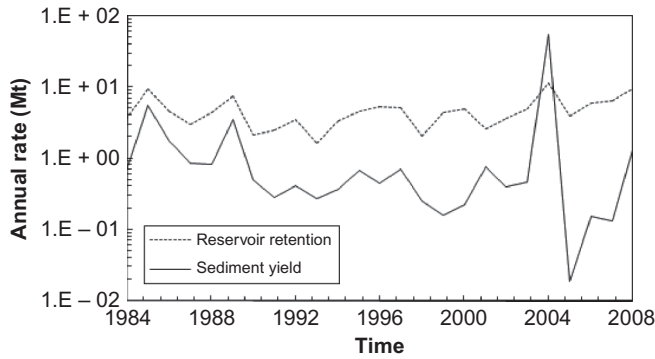


Fig. 7 Time series of global reservoir retention (including the four reservoir classes: C_I, C_{II}, C_{III} and C_{IV}) and sediment yield at the Jaguaribe River control section.

235 t km⁻² year⁻¹ (classes C_I–C_{IV}), which is about 60% higher than the sediment yield at the control section (76 Mt or 148 t km⁻² year⁻¹). The only exception is the year 2004 (see Fig. 7), when sediment discharge surpassed (almost five times) reservoir retention, due to excessive overflow in the whole reservoir network caused by intensive flooding, as observed in three nested watersheds within the UJB (Wiegand, 2009; Medeiros, 2009; Lima, 2010). In contrast, during the driest year of the period, 2005, reservoir retention was more than 200 times larger than sediment yield. Reservoir retention is, therefore, consistently greater than sediment yield, which shows the importance of the network for both sediment yield and sediment distribution in a basin with a HdRN.

As observed by Medeiros *et al.* (2010) in two watersheds within the UJB, the excess rainfall is only notable during extreme flood events, or after sequences of rainfalls, when the hydrological connectivity is high. Thus, in this region, the spatial patterns of overland flow are very similar to those of sediment yield. Therefore, our region can be considered transport-limited. In other climate regions (non-dryland areas), lower variability of reservoir inflows is expected and, as a consequence, different procedures are used for reservoir sizing (see Campos *et al.*, 1997). Hence, in such cases, the average value of the rate of sediment retention $\bar{\xi}_m$ may differ from that obtained in our study, but proportionality between $\bar{\xi}_m$ and rainfall erosivity might also occur.

Figure 8 shows the sediment distribution along the 25-year period in the study area (20 700 km²) and the whole UJB (24 600 km²). In Fig. 8(a), it can be seen that the C_I, C_{II}, C_{III} and C_{IV} reservoir classes retained, respectively, 6, 18, 33 and 5% of the total sediment production (reservoir retention plus sediment yield) in the study area (198 Mt, or 383 t km⁻²

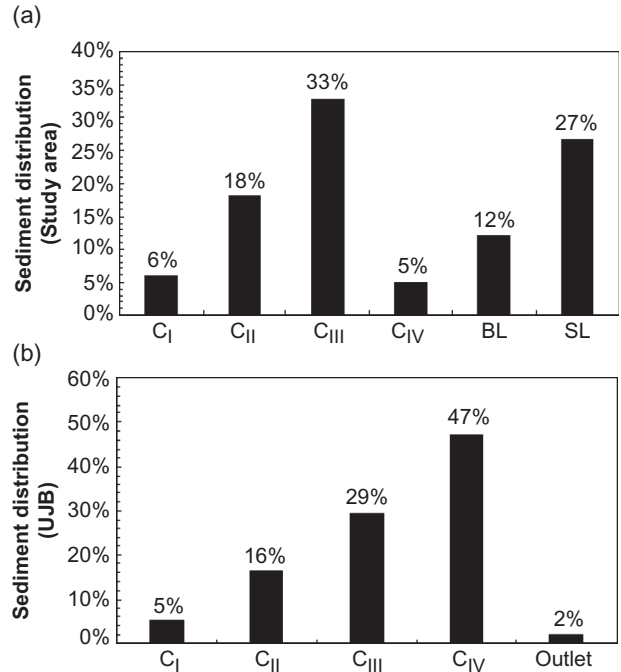


Fig. 8 Sediment distribution along the 25-year period (1984–2008) in the study area: (a) for the control section (20 700 km²); and (b) for the whole UJB (24 600 km²). C_I, C_{II}, C_{III} and C_{IV} represent the four reservoir classes; BL: bed load, SL: suspended load; and Outlet: the sediment discharge in the Orós Reservoir outlet.

year⁻¹), while the bed load and suspended load at the control section corresponded to 12 and 27% of that amount, respectively. Although the percentage of sediment retained in the reservoirs increased consistently from classes C_I to C_{III}, it decreased significantly for class C_{IV}, as the control section is located upstream of the largest reservoir of the basin. Figure 8(b) shows that the inclusion of the reservoirs Trussu (300 hm³) and Orós (2000 hm³) in the sediment balance of the whole UJB increased the contribution of the reservoir class C_{IV} to 47% of the total sediment production in the whole basin (275 Mt, or 447 t km⁻² year⁻¹). The retention in the Orós Reservoir estimated from equation (7) was also compared to the retention estimated using equation (8), giving a difference of only 20%, which confirms the validity of the methodology proposed here to assess reservoir sedimentation. Note that, in equation (8), we used a trap efficiency $T_E = 95\%$, which was obtained from Brune's relationship considering a ratio of 0.8 between reservoir capacity and average annual inflow. This resulted in a sediment yield at the Orós Reservoir outlet of 2% of the total sediment production in the UJB. Figure 9 shows the potential sediment retention as a function of the initial storage capacity for the four reservoir

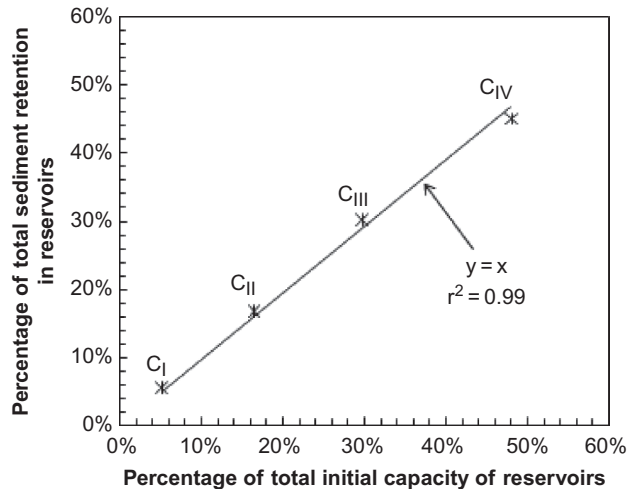


Fig. 9 Potential sediment retention as a function of the initial storage capacity for the four reservoirs classes in the Upper Jaguaribe Basin.

classes in the UJB. A simple linear relationship ($y = x$, $r^2 = 0.99$) was obtained, which suggests that the initial storage capacity is a good parameter to assess the percentage of sediment retention in each reservoir class. This practical result is important to help in the problem of sediment management in basins with a HdRN. Although the methodology proposed here predicted well (20% difference) the retention in the Orós Reservoir, it is not expected to produce accurate estimates of deposition within individual reservoirs, especially the smaller ones, where trap efficiency may vary greatly depending on the catchment area, reservoir size and shape, among other parameters.

The percentages depicted in Fig. 8(b) indicate that the HdRN affects the basin's geomorphology through sediment redistribution in the different reservoir classes (98% of the total sediment production), and may also enhance erosion downstream of the reservoirs, especially at the UJB outlet where a very small amount of sediment (2% of the total sediment production) is discharged. According to the work of Einsele & Hinderer (1997), for a 20×10^3 -km² arid to semi-arid watershed, the sediment yield is expected to be within the range of 300–2000 t km⁻² year⁻¹, whereas the sediment yield of the control section is 148 t km⁻² year⁻¹. Nonetheless, if the sediment retention is considered, the total sediment production rises to 383 t km⁻² year⁻¹, which is in agreement with the results of Einsele & Hinderer (1997). Note that the total sediment production in the UJB is equal to 447 t km⁻² year⁻¹, which is still close to the lower limit (i.e. 300 t km⁻² year⁻¹) of the range above. The relatively low sediment production obtained here is

probably a consequence of flood attenuation (and lower fluvial sediment transport) due to the existence of the numerous reservoirs. However, the HdRN reduces silting of the large (strategic) reservoirs, which would be expected to, at least, double in the case where only such reservoirs existed. This means that retention in non-strategic reservoirs has a positive impact on water availability, since siltation reduces considerably the water yield in semi-arid reservoirs. In order to illustrate that, we estimated the annual percentage storage loss by sedimentation in the Orós Reservoir for two scenarios: (a) considering all the four reservoir classes, as shown in Fig. 1; and (b) considering only the existence of the Orós Reservoir (i.e. neglecting the effect of the smaller reservoirs). For the first scenario, the annual storage loss by sedimentation would be 0.18%, while for the second scenario, it would be 0.48%. This implies that, within 50 years, the Orós Reservoir would lose approximately 8 and 21% of its current storage capacity, according to scenarios (a) and (b), respectively. We can also estimate the impact of siltation on water yield reduction using the methodology described by de Araújo *et al.* (2006). Following that methodology, water yield in the Orós Reservoir with 90% reliability would reduce approximately 27 and 37%, according to scenarios (a) and (b), respectively. Although the other reservoirs evaluated here (see Fig. 6) are potentially being filled up with sediments at an average rate of about 0.2% of their initial storage capacity per year, which is lower than that observed in the world's reservoirs (approx. 1% of the initial storage capacity per year, see Morris *et al.*, 2008), the results above show that the impacts of the HdRN cannot be neglected. This has important implications, since most empirical curves and hydro-sedimentological models used to estimate sediment yield at the basin scale consider only the effect of larger reservoirs (see the Introduction section above).

CONCLUSIONS

We presented a methodology based on rating curves and fitted parameters derived from field data to assess the sediment distribution in a large semi-arid Brazilian basin with a High-density Reservoir Network (HdRN). The bed load and suspended load estimated at a selected river control section were, respectively, 30% and 70% of the total sediment yield in the basin. The relatively low contribution of the suspended load (compared with other semi-arid regions) was attributed to the impact of the dense reservoir network. Micro (<1 hm³), small (1–10 hm³)

and medium-sized (10–50 hm³) reservoirs retained, respectively, 5, 17 and 30% of the total sediment retention by the network, which means that the silting of the large or strategic (>50 hm³) reservoirs would be expected to, at least, double in the case where only such reservoirs existed. Therefore, retention in non-strategic reservoirs has a positive impact on water availability, since siltation reduces considerably water yield in semi-arid reservoirs. The potential sediment retention in the different reservoir classes was also shown to be a linear function of their corresponding initial storage capacity. The HdRN has considerable impact on the basin's geomorphology, since the reservoir sediment retention was about 60% higher than the sediment yield. Hence, at least two processes caused by the dense reservoir network are expected to reduce sediment yield in a large catchment: sediment direct retention and lowering of peak discharges.

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