Impact of a dense reservoir network on water availability in the semiarid north-eastern Brazil

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Abstract The Northeast of Brazil is a semiarid region where water scarcity is a major problem faced by society. Recurrent droughts, which produce serious social-economic consequences, have been dealt with by the construction of dams, allowing the storage of water available in the rainy periods to compensate the deficits during the droughts. Nonetheless, this policy generated a High-density Reservoir Network (HdRN) in the region, resulting in a complex system. A four-step method was used to assess some of the impacts of the HdRN: imagery analysis, hydrological modelling based on field data; sediment budget mostly based on rating curves; and interview application to water managers and users of small reservoirs. The results showed that the existence of a large number of small dams upstream the strategic ones, i.e., those which can supply water throughout long-term droughts, impact both negatively and positively the overall water availability. The negative effects of the HdRN are the high evaporation loss from small reservoirs, which are usually shallower and hydrologically less efficient than the larger ones; and the difficulty in managing the system. On the other hand, the HdRN generates a more democratic water distribution and higher energy rationality, as a consequence of the better spatial distribution of the water resources. In addition, sediment retention in the HdRN leads to lower silting rate (roughly half of the rate, in case the HdRN did not exist) of strategic reservoirs, meaning lower temporal decay in water availability in the already water-scarce region.

Keywords small dams; network; semiarid environment; water availability; sedimentation

INTRODUCTION AND BACKGROUND INFORMATION

Managing water in a dry environment is a challenging task, especially when population density is high, such as in the semiarid North-eastern Brazil. In this environment, groundwater is usually insufficient and/or salty due to the prevailing crystalline bedrock formation in the region, and rivers are intermittent, therefore, decision-makers have, historically, solved the water-scarcity problem by constructing dams. This approach (called the hydraulic solution, see Aragão Araújo, 1990) has prevailed for almost a Century not only by public authorities, but also by community and private initiative, which generated an extremely-dense unplanned network of on-river reservoirs of sizes ranging from 10-2 to 103 Mm3. Strategic reservoirs, i.e., those effective enough to endure a long-term (2 – 4 years) drought, on the other hand, are strongly affected by the construction of thousands of small and middle-sized upstream dams (Malveira, 2009). Because the rivers in the Brazilian semiarid region are intermittent, water availability of a basin controlled by a dam is usually assessed by plotting its yield – reliability curve of the reservoir itself. For this purpose, a long-term water balance is performed using either a historical or a synthetic river-discharge series (McMahon & Mein, 1986; Campos, 1996). Nonetheless, a number of factors can influence the yield-reliability curve of a reservoir (and, therefore, its respective water availability), such as silting (de Araújo et al., 2006), upstream water use (van Oel et al.,

2008) or the construction of upstream dams. Although some authors mention relatively dense reservoir networks in other countries (Rãdoane and Rãdoane, 2005; Pisaniello et al., 2006; Callow and Smettem, 2009), no network comparable (in terms of density) with that observed in the Brazilian semiarid region has been identified in the Literature.

Since the early 1990's, some strategic reservoirs (e.g. Cedro, Poço da Pedra and Várzea do Boi, in the Federal State of Ceará) have not been able to yield their historical discharge, which led to the failure of supplying irrigation projects and/or municipalities. This increasing trend called the attention of water managers, who believed the impact of the reservoir network was the prevailing cause of the failure of such systems. Therefore, the scientific question to be tackled in this paper is: what are the positive and negative effects of such a dense reservoir network on the hydrological performance of the system? The objective of this paper is, after presenting the dense reservoir network in the Brazilian semiarid region, to assess its most relevant impacts on the hydrological performance of a representative basin. The case study was the Upper Jaguaribe Basin (UJB), a 24,167 km^2 area in the western part of the Federal State of Ceará, Brazil.

DESCRIPTION OF THE SEMIARID NORTH-EASTERN BRAZIL

Socio-economic aspects. The Northeast of Brazil is located in a tropical semiarid climate region, also known as the "Drought Polygon" (formalized by the Federal Law nº 175, in 1936), and occupies an area of about one million km2 covering nine Federal States (see Figure 1). Its population surpasses 20 million inhabitants, which makes it one of the most densely populated semiarid regions on earth (de Araújo et al., 2005). The area is much affected by recurrent droughts (statistically one severe drought per decade), as stated by Frischkorn et al. (2003), with serious social-economic consequences. Water scarcity is one of the major problems faced by the society, being a limiting factor for its economic development. De Araújo et al. (2004), who argue that the region already suffers conflicts over water use, demonstrate that this reality may be aggravated by a development scenario characterized by concentrated urbanization and large-scale cash crop irrigation, which has predominated in the last decades. Spatially, an economic gradient can be observed in the region: whilst the richest (relatively more industrialized) municipalities are located on the coast, poverty and underdevelopment prevail as one moves towards the hinterland. The main economic activities of the rural populations are rain-fed agriculture (with predominance of maize and beans) and livestock farming, both for self provision. The mean per-capita Gross Domestic Product (GDP) of the Federal States located in the Northeast region of Brazil was US$ 3,100, whereas the national average was US$ 6,700 and richest regions surpassed US$ 11,000 in 2006 (IBGE, 2009). A discrepancy is also observed in relation to the Human Development Index (HDI): Brazil presented in 2006 a 0.807 HDI, while the mean index of the North-eastern region was only 0.676. Do observe that the above-mentioned GDP and HDI data refer to the whole Northeast region: if one takes only the semi-arid municipalities, indexes are even lower. The Upper Jaguaribe Basin (Figure 2), for instance, is representative of the Brazilian semi-arid region not only in physiographic, but also in socio-economic terms: main economic activities are rain-fed subsistence agriculture and livestock farming, per-capita GDP ranges from US$ 1,200 to US$ 2,700 and HDI ranges from 0.560 to 0.692 (IBGE, 2009).

Physiographic aspects. The climate on the region is of the type 'BS', according to

Köppen classification (de Araújo & Piedra, 2009). Mean annual precipitation ranges from 400 to 800 mm.yr^{-1}, whilst potential evaporation measured in class-A pan can reach up to 2,500 mm.yr^{-1}, producing high atmospheric water deficit. The aridity coefficient (precipitation to potential evaporation rate) ranges from 0.25 to 0.35, whereas in humid tropical regions it can be as high as 0.70 (de Araújo and Piedra, 2009). Rainfall temporal variability is high, with almost 80% of the total annual depth being concentrated in the rainy months (January – April). Mean annual temperature is 25°C, with low variation throughout the year, from 23°C to 28°C. Annual sunshine reaches 2,800 hours and relative humidity is of the order of 50% (de Araújo et al., 2004). The predominant vegetation type in semiarid Brazil is Caatinga, a deciduous forest composed of a mixture of cacti, bushes and trees not higher than 10 m, whose interception losses (16%) are up to three times higher than average runoff (Medeiros et al., 2009). Frequently, the natural vegetation has been replaced by livestock farming and agricultural activities. Soils in the region are shallow, with depths of the order of 1 m, under which crystalline bedrock occurs. The main hydrological consequence of this feature, in association to the high temporal variability of the rainfall, is that its rivers are intermittent, with coefficient of variation of annual river discharges as high as 1.4. In addition, there is no significant groundwater storage. Runoff coefficients are low, typically between 5% and 12% (Campos et al., 1997; de Araújo and Piedra, 2009), but values as low as 3% have been measured in some middle-sized watersheds (10^3 km^2, see Medeiros et al., accepted). A combination of factors is responsible for this behaviour: evaporation rates are higher than rainfall depths during long periods, rainfall can be localized and vegetation is sparse. As a consequence, saturation of the top soil layers is discontinuous in space and time, allowing re-infiltration of the overland flow and limiting the water fluxes from the hillslopes to the river network, as described by Puigdefabregas et al. (1999) for the Spanish semiarid region. Therefore, runoff along the rivers is limited to a few days during the year, especially after a sequence of rainfall events, when the soils reach high water content and hydrological connectivity is enhanced (Medeiros et al., accepted).

The High-density Reservoir Network (HdRN). In order to minimize the effects of water scarcity caused by the adverse natural conditions, Federal, State and Municipal Governments (as well as community and private initiatives) have implemented a robust hydraulic infrastructure, focused on on-river dams of all sizes: large (storage capacity larger than 50 Mm^3), middle-sized (10 – 50 Mm^3), small (1 – 10 Mm^3) and micro (storage capacity lower than 1 Mm^3) (Aragão Araújo, 1990). This strategy was expected to enhance water reliability in the periods of droughts (ranging typically from 8 months to 3 years). Despite the high evaporation rates, resulting in a loss of large volumes of water to the atmosphere (up to 50% of inflow discharges: Campos, 1996), surface reservoirs are the most important water sources in the semiarid Northeast of Brazil. According to de Araújo et al. (2005), such structures are responsible for 90% of the water supply in Ceará. Nonetheless, the construction of the HdRN also led to critical situation in some watersheds. For instance, some large reservoirs, such as Cedro (126 Mm^3), Várzea do Boi (52 Mm^3) and Poço da Pedra (51 Mm^3), took several consecutive decades to refill, forcing water authorities to change their strategies to reach a favourable water balance in the respective municipalities. The micro and small dams have been historically constructed either by the private sector or by the Dam Cooperation Program (DCP), a governmental initiative in which the public sector builds the dam and the land-owners donate the area in which it will be built (Aragão Araújo, 1990). According to the Brazilian constitution, water is a public good and the owners of cooperation dams should be obliged to allow open access to its waters,

Fig. 1 Location map of the Droughts' Polygon in Brazilian North-eastern region.

which not always happens. One of the oldest infrastructure governmental programs in Brazil, the DCP has been used integrated with the Drought Policy of the Country: in dry years, unemployed agriculture workers are hired by governmental agencies to build infrastructure systems, which include roads and dams. This means that, in dry years, the construction rate of small dams usually increased considerably. More recently, nonetheless, water management agencies have been concerned about the increasing number of dams in the region.

METHODS

In order to investigate the positive and negative impacts of the HdRN, four major steps have been taken: (i) imagery analysis of the UJB; (ii) hydrological modelling based on field monitoring; (iii) sediment budget analysis; and (iv) interviewing decision makers and small-reservoirs users. Airplane images taken in the year 1970 (scale 1:100,000), as well as Landsat images of the year 2002 were used to analyse the occurrence of on-river reservoirs in the Upper Jaguaribe Basin (Malveira, 2009). Volumes of the official ones were given by the DNOCS data base, whereas the volumes of the unofficial ones were assessed using the Molle (1989) empirical relation, based on measurements of 416 small dams in the Brazilian semiarid region (equation 1):

$$V_{oT} = \acute{a}h(A)^{\acute{a}/2} \qquad (1)$$

In Equation (1), h is the maximum water height (m), function of the flooding area A (m^2); and α_1 and α_2 are parameters. The measurement-modelling effort tackled the scale problem by monitoring and modelling three nested watersheds: the Aiuaba Experimental Basin (AEB, 12 km^2), which is located within the Benguê Basin (BB, 933 km^2), located within the Upper Jaguaribe Basin (UJB, 24,167 km^2). The monitored variables were mainly rainfall (80 gauges within the UJB), reservoir level (seven reservoirs), river discharges (one gauge section at AEB, one at BB and one at UJB) as well as sediment suspended load and bedload (in the same river sections). The long-term (average 70 years) siltation of nine reservoirs (sizes from $6x10^{-2}$ to $1x10^{2}$ Mm^3) has been performed by comparing initial volume-height curves with those generated by updated bathymetric surveys. For further information on monitoring strategies, please refer to de Araújo et al., 2003; Wiegand, 2009; Malveira, 2009; and Medeiros, 2009. The hydrological behaviour of the basins was analyzed using the Water Availability in Semi-Arid Environments Model – WASA (Güntner, 2002; Güntner and Bronstert, 2004). WASA is a deterministic, semi-distributed daily-step model, which represents the main hydrological processes of dry environments: precipitation (independent variable), interception, soil evaporation, infiltration, surface runoff, percolation, lateral subsurface flow and aquifer recharge. Spatially, the model uses five hierarchical levels: the sub-catchment, the landscape unit, the terrain component, the soil-vegetation component and the soil profile. The WASA model is also able to deal with dense reservoir networks by considering some explicit and some non-explicit reservoirs. The explicit reservoirs are those controlling sub-catchments outlets (whose individual parameters are provided), whereas non-explicit reservoirs are dealt with statistically. These are divided into five size classes, each one of which is simulated by a representative dam, whose parameters must be provided. The model assumes that smaller reservoirs are located upstream larger ones. Although this might not be strictly true in some watersheds, the assumption does not distort the overall water balance, as shown by de Vries (2006).
The sediment budget, on the other hand, used the rating-curve approach, based on field data. The temporal monitoring lengths of the field data (used to generate the rating curves) were as follows: water discharge at AEB (2003 – 2009), at BB (2000 – 2009), at UJB (1912 – 2009); suspended sediment discharges and bedload at AEB (2003 – 2009), at BB (2005 – 2009), at UJB (rainy season of 2009). Although water discharge and suspended sediment used direct rating curves, bedload was estimated using the modified Meyer-Peter and Müller equation (apud García, 2008):

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

In Equation (2), q* is the dimensionless bedload transport rate given by $q^* = q_b / D\sqrt{gD\lambda}$, τ^* is the dimensionless shear stress (Shields parameter), dependent on the energy line slope of the channel; qb is the volumetric bedload transport rate per unit width ($m^2.s^{-1}$); 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. The last methodological step was to apply simple open interviews to decision makers and small-reservoirs users. Decision makers are usually concerned with the largest systems, whereas the interviewed users rely on micro (storage capacity lower than 1 Mm^3) and small (1 – 10 Mm^3) reservoirs for producing and living. The interviews were made with technical personnel from three institutions: the National Department of Works against Droughts – DNOCS, the Ceará State Secretariat for Water Resources – SRH, and the Ceará State Water Management Company. The interview was also applied to 100 users of 20 micro and small reservoirs located within the Upper Jaguaribe Basin.

RESULTS AND DISCUSSION

The HdRN characterization in the UJB. The assessment of the temporal evolution of the HdRN in the Upper Jaguaribe Basin showed that, whereas in 1970 there were 2,174 dams in the basin, in the year 2002 there were already 4,014 of them (Figure 2). Among those, only seven are considered strategic, i.e., dams with capacity larger than 50 million m3, which can supply water throughout long-term droughts (2 – 4 years). This means that presently the density of micro, small and middle-sized dams is so high that the average direct catchment area is less than 6 km^2. The hydrological simulation of the last five decades using WASA showed that surface runoff averages 1.6 billion m^3 per year, whereas storage capacity is presently close to 8 billion m3. This gives an impoundment ratio of about 5 or, reinterpreting the parameter, this gives an average residence time of about 5 years. This result is consistent with the monitored level of the dams, which show that the strategic dams overspill at a frequency of 4 to 5 years. The DISPAB Research Project (DISPAB, 2009) is presently investigating the small dams in three Brazilian Federal States and showed that, in some meso-scale (10^2 – 10^4 km2) semiarid basins within the States of Paraíba and Rio Grande do Norte, the average direct catchment area is as low as 1 km^2.

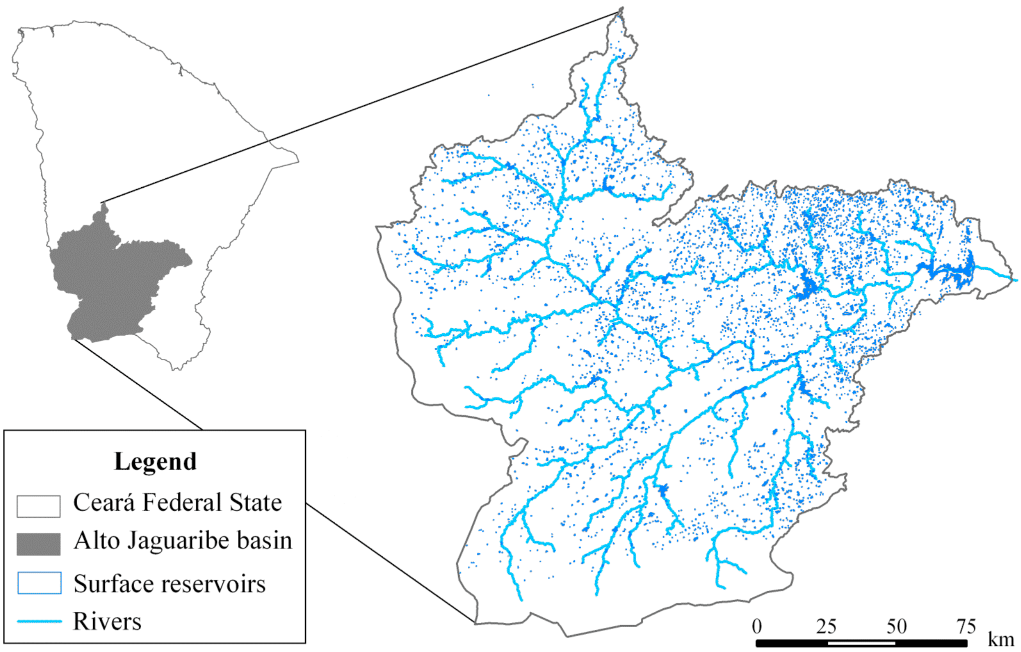

Fig. 2 Spatial distribution of 4,014 dams (year 2002) in the Upper Jaguarine basin, in the Federal State of Ceará, Brazil. Source: Malveira, 2009.

Negative aspects of the HdRN: excessive evaporation and integrated water management. The two main drawbacks of the High-Density Reservoir Network (HdRN) are its excessive evaporation discharge and the difficulty of integrated water management. Monitoring results show that potential (class-A pan) evaporation in the Brazilian semiarid region averages 2.5 m annually. This can be up to four times higher than its respective rainfall rate, as in UJB. It is clear that evaporation discharge enhances considerably when small shallow reservoirs are constructed. The results of the hydrological model for the Upper Jaguaribe basin show that the fourteen largest reservoirs (out of 4,014 in the year 2002) are responsible for more than 50% of the water storage capacity and more than 75% of high-reliability yield. The evaporation discharge in the remaining 4,000 dams is, on the other hand, almost as high as in the fourteen largest ones. For that reason, many decision-makers, during the interviews, suggested that a reasonable policy would simply be to prohibit further construction of small shallow dams, as well as to destroy many of the existing ones. Another flaw of the HdRN is the difficulty in managing (and even in modelling) such a complex system, according to the interviews. The water management institutional system in Brazil consists of Water Councils (State or Federal, depending on the domain of the water), Water Committees and Water Agencies. Such institutions are related with large basins and tend to take only the largest reservoirs into consideration, which was confirmed by most of the decision makers. Nonetheless, more than 90% of the interviewed small-reservoirs users outlined the economical, social and environmental importance of the micro/small dams for the diffusive rural population of the Brazilian semiarid region. For that reason, a new strategic plan for the small systems is being developed by researchers of four Brazilian Federal Universities (DISPAB, 2009). According to the plan, small systems would have a Water Commission and would count on a large regional data-base, which should be used for assessing relevant hydrological variables either by direct measurements or by modelling (parameters regionalization). One of the main tasks of the commissions should be to care for the water quality, according to the small-dam users. These reservoirs are very vulnerable to eutrophication processes, mainly due to mismanagement of its catchment (de Araújo, 2000), such as cattle direct access to the reservoirs. This leads to lower water availability in an already water-scarce environment: many communities search water in larger dams several kilometres away when their reservoirs are polluted.

Favourable aspects of the HdRN: water distribution, energy rationality and sediment retention. It is remarkable, though, that the numerous small dams also present some hydrological advantages, such as better spatial distribution of the water. Land in Brazil (and especially in the Northeast of the country) is highly concentrated (Brito, 2006) and so is access to water, which has been historically associated with land owners. Therefore, the existence of thousands of small dams within the HdRN means the access to water for the poorest families, as confirmed by the users in the interviews. Another positive aspect of the HdRN is that it saves a considerable amount of energy: had there not been the numerous upstream reservoirs, water would have to be pumped from the more hydrologically effective downstream reservoirs to the users located in higher altitudes (see discussion on the ‘downstreamness’ concept in van Oel, 2009).

Concerning the sediment balance of the UJB, the analysis has been performed by differentiating the reservoirs into four classes: the micro (storage capacity lower than 1 Mm^3); the small (1 – 10 Mm^3); the middle-sized (10 – 50 Mm^3); and the large (> 50 Mm^3) ones. The applied methods showed that sediment inflow discharge at the four reservoir classes (see Figure 3, in which class I are the micro; class II the small; class III the middle-sized; and class IV the large reservoirs) in the study area agree (in terms of trend) with the sediment discharge (suspended sediment plus bedload) in the Jaguaribe River, although the curves have been obtained by fully independent methods. The global sediment production (i.e., the summation of reservoir sedimentation rate and river sediment discharge), considering the last 25 years, averages 393 $t.km^{-2}.yr^{-1}$ at the UJB. Out of that, 6% was trapped in the micro; 18% in the small; 32% in the middle-sized; 42% in the large reservoirs; whereas 2% flow from the outlet control reservoir (Orós dam, 2,100 Mm^3). This means that, without the micro, small and middle-sized reservoirs, siltation of the large (usually strategic) ones is expected to, at least, double. In the Federal State of Ceará, in Northeast Brazil, the loss of storable volume corresponds to 1.85% per decade (de Araújo et al., 2003), which causes water yield reduction of almost 1.5% per decade (de Araújo et al., 2006). Even thought the siltation rate in the region seems to be of less importance, it should be kept in mind that in a reality of water scarcity, any reduction of water availability represents a demand that might not be met. The sediment budget shows the importance of the non-large dams on water availability: the strategic dams receive less than half of the sediment yield of its catchment, which means that its useful life is much longer than it would be had there not been the HdRN upstream. In other words, due to the micro, small and middle-sized dams, the high-reliability water yield decreases at a much lower rate.

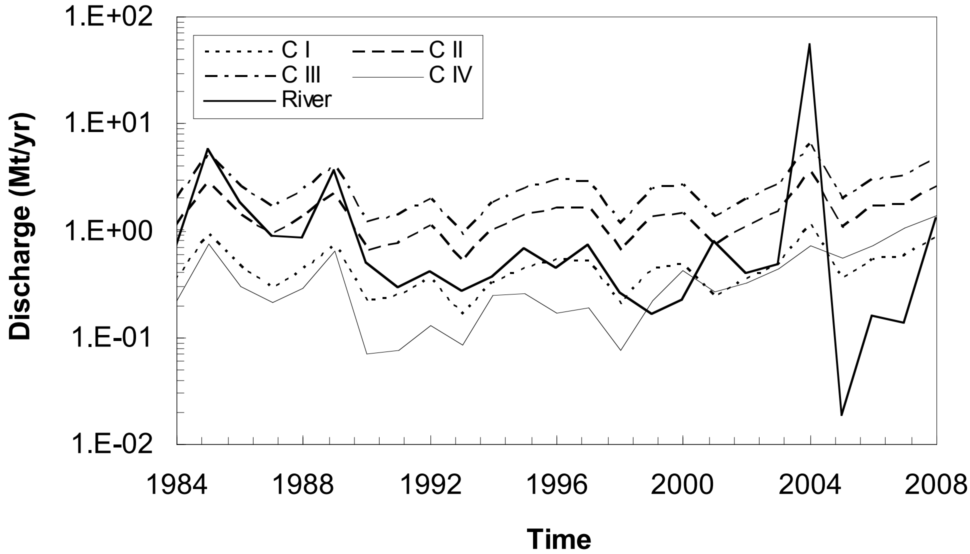

Fig. 3 Time series of yearly sediment discharge at the four reservoir classes in the study area and at the Jaguaribe River just upstream the Orós dam. Class I includes the micro (storage capacity lower than 1 Mm^3); class II the small (1 – 10 Mm^3); class III the middle-sized (10 – 50 Mm^3); and class IV the large (> 50 Mm^3) reservoirs.

CONCLUSIONS

The main conclusions that can be drawn from this study, led in the semiarid Upper Jaguaribe Basin, in the Federal State of Ceará, Brazil, are:

(i) The existence of the high-density reservoir network is a reality in the semiarid Northeast of Brazil, with both positive and negative impacts on water availability. Such a dense reservoir network has not been identified in any other region (semiarid or not) in the Literature;

(ii) The results showed that the two main negative impacts of the HdRN are the excessive evaporation discharge from the surface reservoirs (which leads to the reduction of water availability) and the increasing complexity of the system to be managed;

(iii) The studied HdRN presented, nonetheless, some positive impacts, such as better water distribution, which allows diffusive rural population to benefit from the water system; energy rationality, once gravity centre of the water offer is higher than it would be without the network; and sediment trapping, which leads to lower silting rate (and lower water availability decay) of the strategic dams.

Therefore, the high-density reservoir network has proven to be a strongly non-linear problem to be solved by the Brazilian north-eastern society. An integrated analysis of the before-mentioned aspects, which was not accomplished in this research, is highly desirable.

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