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NeStRes – Model for Operation of Non-Strategic Reservoirs for Irrigation in Drylands: Model Description and Application to a Semiarid Basin

Paulilo Brasil[1] · Pedro Medeiros[2]

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Abstract
Water availability in dry inhabited environments has usually been promoted by large strategic reservoirs, but small non-strategic ones, built by farmers and communities, are unable to cope with long term droughts and inappropriate for human supply. Nevertheless, small reservoirs promote water spatial distribution and play a major role for livelihood in rural areas. To fill the gap of operation methods for non-strategic reservoirs used for irrigation where water is a limiting factor, the NeStRes model was developed. The model is composed of three modules: i) hydrological: to define the reliability of water withdrawals from the reservoir; ii) agricultural: to simulate crop production based on water availability; iii) economic: to compute the possible income from irrigated agricultural crops. NeStRes was applied to 91 reservoirs of the semiarid Banabuiú River Basin – BRB, Brazil. The simulations indicated that the maximum income from the cultivation of maize is obtained when the reservoirs are intensely used, drying completely in one to two thirds of the time. Adoption of a fixed reliability level of daily water supply (54%, in the BRB) generates at least 85% of the maximum possible income for all simulated reservoirs. This model application suggests a paradigm change in the operation of small non-strategic reservoirs in drylands: to use water for crop production and save the revenue, instead of saving water, which is susceptible to evaporation. Although high reliability level is desired for human supply by strategic reservoirs, non-strategic ones can be more intensely explored to generate income from irrigated agriculture in drylands.

Keywords Reservoir operation · Water scarcity · Irrigation · Drylands

✉ Pedro Medeiros
phamedeiros@ifce.edu.br

[1] Department of Agricultural Engineering, Federal University of Ceará, Centro de Ciências Agrárias - CCA/UFC, Bloco 804, s/n - Pici, Fortaleza, CE 60455-760, Brazil

[2] Federal Institute of Education, Science and Technology of Ceará, Av. Parque Central, 1315 - Distrito Industrial I, Maracanaú, CE 61939-140, Brazil

1 Introduction

Water scarcity in inhabited dry environments imposes the adoption of practices for the coexistence of humans with droughts, the construction of dams being amongst the most popular measures for water supply in such conditions (van der Zaag and Gupta 2008). Storage of the excess water during wet seasons for supply during water shortages has proven to be effective in water scarce regions (Campos 2015), but some adverse effects may arise. For instance, enhancement of water availability may promote an increase in the water demand in drylands, where water is a limiting factor for economic development, and the benefits of reservoirs may be quickly offset (Di Baldassarre et al. 2018). Additionally, the positive effects of large reservoirs built by the public sector lead farmers and remote communities to build their own small reservoirs, which can generate high-density networks (Mamede et al. 2012), contributing to the decentralization of water supply (van der Zaag and Gupta 2008) but also impacting the streamflow (Habets et al. 2018) and the larger strategic reservoirs located at downstream positions (Krol et al. 2011; Mamede et al. 2018).

Despite the recognized importance of reservoirs to reduce the frequency of hydrological droughts, liability of society in such structures increases vulnerability, which can potentialize the negative effects of droughts (Di Baldassarre et al. 2018), leading to the system collapse if the reservoirs run dry (Kuil et al. 2016). Therefore, reservoir operation plays a major role on the sustainability of coupled human-hydrological systems in drylands. To reduce the probability of water supply failures, reservoirs for human supply are usually operated with high reliability level in accordance with the practice of "saving water" (Campos 2010).

On the other hand, as the reservoir capacity of converting inflow into water withdrawal tends to increase with catchment size and reservoir storage capacity (Campos 2010), the small systems cannot cope with long-term droughts (de Araújo and Bronstert 2016). Hence, keeping water in small non-strategic reservoirs under intense evaporation rates lead to high relative losses (Campos et al. 2016) and inefficient water use from these sources. Because of their low relative hydrological efficiency, associated to data scarcity in that scale (Zhang et al. 2016; Pereira et al. 2019), small reservoirs are usually not considered in the water management policies (Gutiérrez et al. 2014) and frequently underused. However, such structures play a major role for livelihood in rural areas of dry regions such as the sub Saharan Africa (Fraiture and Giordano 2014) and the Northeastern Brazil (de Araújo and Bronstert 2016).

Acknowledging that each reservoir has a specific role in the system, reservoir operation must consider this heterogeneity according to the hydrological potential and the reliability level required by the demand type. Numerous methods have been presented for operation of large strategic reservoirs (Loucks and van Beek 2017), still less attention has been given by the scientific community to the small ones serving remote, rural populations (Sanfo et al. 2017; Ouyang et al. 2018). To fill the gap of methods for operation of small non-strategic reservoirs used for irrigation in water scarce regions, the NeStRes model (Model for operation of Non-Strategic Reservoirs for irrigation in drylands) was developed.

The main goal of the NeStRes model is to define criteria for a more rational operation of non-strategic reservoirs, focusing on small scale irrigated agriculture and considering water as a limiting factor. The model is composed of three routines: i) hydrological module to define the reliability of water withdrawals from the reservoir; ii) agricultural module to simulate crop production based on the available water; iii) economic module to compute the possible income from irrigated agricultural crops.

In addition to the NeStRes model description, in this work we present an application to 91 reservoirs with various sizes (3.5×10^5 to 1.7×10^7 m^3 storage capacities) in the semiarid meso-scale Banabuiú River Basin (19,800 km^2 of extension), in northeastern Brazil.

2 Material and Methods

2.1 NeStRes Model Description

NeStRes is a model for the operation of small non-strategic reservoirs for irrigation purposes in drylands, aiming at maximizing the income from small scale agriculture. The concept behind it is to assess the trade-off between water evaporation and withdrawal for irrigation, considering the risk of crop loss. The practice of saving water for continuous irrigation reduces the risk of water shortage, but promotes high evaporation losses and low conversion of the inflow into withdrawal, negatively impacting crop production. On the other hand, intense water use enables the irrigation of larger areas, but increases the risk of reservoir emptying, which may result in crop loss due to water deficit during the crop cycle.

The model simulates the agricultural arrangement based on reservoir dynamics, admitting that water is the limiting factor. In the hydrological module, water availability is assessed by computing the reservoir temporal dynamics (Eqs. 1 to 3, de Araújo et al. 2006):

$$\frac{dV}{dt} = Q_{in}(t) - Q_{out}(t) \tag{1}$$

$$Q_{in} = Q_R + Q_P + Q_G \tag{2}$$

$$Q_{out} = Q_E + Q_I + Q_S + Q_W \tag{3}$$

Where: dV (m^3) is the variation of the stored volume during the time interval dt; Q_{in} is the sum of all inflows (runoff - Q_R, direct precipitation on the lake - Q_P; underground recharge - Q_G); and Q_{out} is the sum of all outflows (evaporation - Q_E, infiltration - Q_I, spillage - Q_S, withdrawal for water supply - Q_W), all flows being calculated in m^3/day. For model application in the Banabuiú River Basin (see section 2.3), seepage and underground recharge are admitted negligible according to previous works (de Araújo et al. 2006; Campos 2010).

Water availability is estimated by simulating different withdrawals (Q_W), which provides pairs of reservoir water yield and the respective reliability level. The reliability level of daily water supply is computed according to Eq. 4.

$$G = 1 - (n_u/n) \tag{4}$$

Where: n is the total number of days in the simulation; and n_u is the number of unsuccessful days, i.e. days in which the desired water withdrawal cannot be provided.

Reservoir geometry is represented by power functions fitted to measured water height-area-volume curves (see Pereira et al. 2019):

$$V = K \cdot h^{\alpha} \quad (5)$$

$$A = \alpha \cdot K \cdot h^{(\alpha - 1)} \quad (6)$$

Where: V is the reservoir volume (m^3); A is the flooded area (m^2); h is the water level (m); K and α are the aperture and shape coefficients, respectively. It is shown from Eqs. 1 to 6 that water withdrawal and evaporation are competing outflows: higher withdrawal reduces the reservoir volume and the flooded area, consequently promoting lower water loss due to evaporation, and vice versa (see for instance, Campos et al. 2016).

In the agricultural module, crop water balance is calculated in a daily timestep, considering the management of irrigation via climate, i.e. the computation of water fluxes in the root zone, based on climatic variables, to define the amount to irrigate. The model considers irrigation and precipitation as the input components, while the losses by deep percolation, surface runoff, evaporation and water consumption by the plants (evapotranspiration) are the output components. With adequate management during water deficit periods, in which irrigation is promoted as to achieve field capacity, runoff, deep percolation and direct evaporation can be eliminated, with irrigation, precipitation and evapotranspiration remaining.

The reference evapotranspiration is estimated using the parsimonious equation proposed by Hargreaves and Samani (1985, Eq. 7):

$$ET_{0i} = 0,0023 \cdot \left(T_{\max,i} - T_{\min,i}\right)^{0,5} \cdot \left(T_{av,i} - 17,8\right) \cdot Ra_i \cdot 0,408 \quad (7)$$

Where: ET_{0i} is the reference evapotranspiration (mm); $T_{max,i}$, $T_{min,i}$, and $T_{av,i}$ are the maximum, minimum and average temperatures (°C), respectively; and Ra_i is the solar radiation at the top of the atmosphere ($MJ.m^{-2}$), all variables for day i.

The crop evapotranspiration is calculated using Eq. 8:

$$ETc_{ik} = ET_{0i} \cdot Kc_{ik} \quad (8)$$

Where: ETc_{ik} is the evapotranspiration of crop k on day i (mm) and; Kc_{ik} is the crop evapotranspiration coefficient for crop k on day i (dimensionless).

Time variable irrigation is defined as to raise the soil water content to the field capacity before the crop is under water stress. The irrigation condition is that soil moisture is equal to or less than the readily available water (W_{RA}, Eq. 9), that is, it can be extracted from the soil without water deficit to the crop. W_{RA} is calculated as a percentage of the maximum available water in the soil (W_{max}, Eq. 10).

$$W_{RA} = f \cdot W_{\max} \quad (9)$$

$$W_{\max} = (\theta_{FC} - \theta_{WP}) \cdot (\rho_s / \rho_w) \cdot Z_{RD} \quad (10)$$

Where: W_{RA} is the water readily available to plants (mm); f is the fraction of soil water depletion (dimensionless); W_{max} is the maximum water availability in the soil (mm); θ_{FC} and θ_{WP} are the soil moistures at field capacity and at wilting point (%), respectively; ρ_s and ρ_w are the soil and water densities ($g.cm^{-3}$); Z is the depth of the root zone (mm).

The total water availability in the soil on day i (d_{ws_i}) is computed from the water available in the beginning of day i (d_{ws_0}), crop evapotranspiration in the previous day (ET_{Ci-1}), precipitation of day i (P_i) and the net irrigation depth of the previous day (d_{nir_i-1}), all variables in mm (Eq. 11).

$$d_{ws\_i} = d_{ws\_0} - ET_{Ci-1} + P_i + d_{nir\_i-1} \tag{11}$$

The net irrigation depth (d_{nir_i-1}) is defined as the requirement for the soil to reach the maximum water availability (W_{max}), and the adoption of irrigation depends on the water availability in the soil (d_{ws_i}), according to Eq. 12.

$$\text{If } d_{ws\_i} \leq W_{RA}, \text{then } d_{nir\_i} = W_{\max} - (d_{ws\_i} - ET_{Ci}), \text{otherwise } d_{nir\_i} = 0 \tag{12}$$

Withdrawal from the reservoir for irrigation on day i (Q_{W_i}) is computed by the product of the gross irrigation depth required on day i (d_{gir_i}) to avoid water stress in the crop, by the maximum area available for cultivation (A_{max}, Eq. 13). The gross irrigation required on day i (d_{gir_i}) is given by the ratio of the net irrigation required on day i (d_{nir_i}) by the efficiency of the irrigation system.

Admitting that water is the limiting factor, the maximum area available for cultivation is defined at the onset of the crop cycle and considering the water volume stored in the reservoir, thus avoiding loss of crop production due to water shortage during the cycle.

$$A_{\max\_ijk} = Max\left\{ Min\left[\frac{V_{ij} - \left(\frac{A_i}{2} \cdot Ev \right)}{1.1 \cdot tc_k \cdot q_{d\_k}}; \frac{Q_{w\_j}}{q_{d\_k}} \right]; 0 \right\} \tag{13}$$

Where: A_{max_ijk} is the maximum area for cultivation on day i, reliability level of water supply j and crop k (m^2); V_{ij} is the water volume stored in the reservoir on day i for reliability j (m^3); A_i is the area flooded by the reservoir on day i (m^2); Ev is the annual evaporation (m); tc_k is the number of days of the crop k cycle (day); q_{d_k} is the crop water demand per area of cultivation ($m^3.m^{-2}.day^{-1}$) and; Q_{w_j} is the available flow supplied by the reservoir, for reliability level j ($m^3.day^{-1}$).

The irrigation depth is variable in time, thus the volume of water to be withdrawn from the reservoir for irrigation on day i (Q_{W_i}) is not constant, i.e., the volume of water stored in the reservoir is subtracted from Q_{W_i} at the end of each day when irrigation is required.

The economic module computes a balance considering the costs and revenues of the agricultural production system. The costs refer to production (soil preparation, seeds, pesticides, labor); electricity; and initial acquisition cost of the irrigation system. Degradation of the infrastructure along time is considered by admitting that the equipment and pipes should be replaced every 10 years and introducing such costs in the simulation. The revenue corresponds to the value obtained from the production sale at the end of the crop cycle, admitting a fixed price ($\$.kg^{-1}$) of the product.

The economic simulation is performed monthly and applies an interest rate to the accumulated value when it is negative, whereas for positive balances, a return rate is considered. Based on this arrangement, a fixed income value is optimized until the balance is equal to zero at the end of the simulation, allowing for positive and negative fluctuations. Taken over long periods, the simulation reproduces the hydrological variability and its impact on the crop production, making it possible to define the outcomes of each reservoir operational rule for current conditions.

The entire abovementioned procedure is repeated for different reliability levels of water supply, i.e. for different water availability scenarios. Consequently, monthly incomes are obtained for each reliability, crop and irrigation system used in the simulations, supporting the farmers' decision on what combination to adopt.

2.2 Model Application

The NeStRes model was applied to 91 reservoirs (storage capacities from 3.5×10^5 to 1.7×10^7 m^3) located in the tropical Banabuiú River Basin (BRB), with approximately 19,800 km^2 in northeast Brazil (Fig. 1). According to Köppen climate classification, the basin is hot semiarid (BSh), with monthly average temperatures ranging from 25 °C to 29 °C, average rainfall and potential evaporation of the order of 750 mm and 2500 mm per year (INMET 2018). Rainfall is highly time-variable (Medeiros and de Araújo 2014): the rainy season is concentrated from February to May, accounting for 75% of the annual rainfall, and an average of 36 days per year with rainfall higher than 5 mm.

Geologically, BRB is characterized by the occurrence of crystalline basement, with very limited and spatially heterogeneous groundwater availability. Soils are generally shallow, with depths of the order of 1 m, which in association to the climatic features, result in intermittent rivers. Temporal variability of streamflow is very pronounced (Figueiredo et al. 2016), and the coefficient of variation for average annual rivers' discharges is of the order of 1.4.

The high temporal variability of water availability has led to the construction of dams, generating a very dense reservoir network with over 1000 reservoirs with surface areas larger than 5 ha (Pereira et al. 2019). The conservative practice of saving water in reservoirs prevails, a cultural value resulting from: 1) the severe socio-economic impacts of droughts in the past; 2) operation of reservoirs with high reliability, introduced by technicians for human-supply strategic structures and appearing as guideline regardless of the water uses. However, most of the small reservoirs are unable to cope with long-term droughts and fall empty due to the high potential evaporation rates, in spite of any water use by the population. Such reservoirs are, therefore, unsuitable for human supply, but can be used elsehow. For instance, the

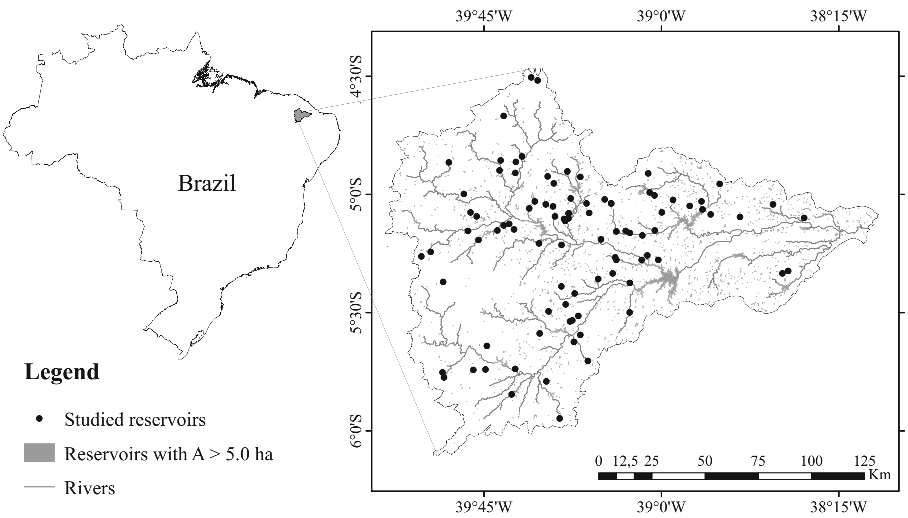

Fig. 1 Banabuiú River Basin and the studied reservoirs

reservoir network enables to establish priority uses of each structure in accordance with the hydrological efficiency, supplying humans and livestock from those with high reliability. In this context, the remaining thousands of small reservoirs could be more efficiently explored to generate income.

In this study, 91 non-strategic reservoirs were simulated (Fig. 1) over a period of 108 years (1910–2017), to which daily rainfall data was available for four rain gauges in the basin (ANA 2018). Other climatic data, i.e. evaporation, maximum and minimum temperature, were taken as the monthly averages recorded in two climatic stations located in the BRB (INMET 2018). Daily inflow to the reservoirs (Q_R, in Eq. 2) was computed by applying the Curve Number (CN) empirical method (USDA 1986), using the abovementioned rainfall timeseries. The unique parameter (CN) of the model was calibrated based on streamflow timeseries available for two stream gauges, fitting the overall modelled runoff coefficient in the respective catchments to the measured ones.

The crop adopted in the simulations was maize (*Zea mays*), the most expressive cereal grown in Brazil (over 80 million tons produced in an area of approximately 16.6 million hectares in the 2017/2018 harvest – CONAB 2018) with cultivars adapted to the semiarid climate of the BRB. According to the soil types of the basin, a representative soil with the following properties was considered: moisture at field capacity (θ_{FC}) of 22%, moisture at wilting point (θ_{WP}) of 10% and density (ρ_s) of 1.4 g.cm^{-3}.

The crop cycle was considered 110 days, with 10 more days for soil preparation and replanting, totaling a 120 days cycle. It was admitted that 3 cycles of maize per year are possible if there is enough water in the reservoir for irrigation. To define the maximum irrigable area in the onset of each cycle, the crop water demand was admitted equal to 650 mm per cycle, regardless of the seeding period. During the simulations, however, water is supplied preferentially by rainfall and only complemented by irrigation. This conservative criterion aims to avoid crop loss due to water shortage during the cycle.

Maize productivity in Brazil is in the range of 6 to 10 Mg.ha^{-1} according to the Brazilian National Food Supply Company (*Companhia Nacional de Abastecimento* – CONAB), a productivity of 8,5 Mg.ha^{-1} being considered in the simulations. The production costs were set as average values representative of irrigated maize fields with medium technological level in Brazil. Irrigation was defined as sprinkler type with 75% efficiency, which has shown to be met in small rural properties in the study area with appropriate management.

In the economic module, a 0.65% monthly return rate was considered, according to the profitability of saving accounts in Brazil, and a 10% annual interest rate was applied to negative balances, in accordance with financing conditions applied to the agriculture sector. The best reservoir operation criterion adopted in this work was that providing highest income obtained from the proposed arrangement of irrigated agriculture.

To assess the role of the variables and parameters in the model results, a sensitivity analysis was performed. The climatic (evaporation and precipitation), agricultural (length of the cycle and water demand of the crop) and economic (sale price, interest and return rates) factors were varied in the range of −50% to +50%, observing the changes in the income and the reliability on daily water supply.

A specific reservoir, representative of the average conditions of our sample and well known by us from previous studies (for instance, Zhang et al. 2016), was chosen for the sensitivity analysis. The storage capacity of the São Joaquim reservoir is 5,1 hm^3 and it is within the applicability range of the NeStRes model (see next section). The values used as reference (0% variation) in the simulations are:

- Climatic factors: 750 mm and 1990 mm annual precipitation and potential evaporation, respectively;
- Agricultural factors: 110 days cycle and 650 mm water demand of the maize crop;
- Economic factors: corn sale price of 235 US$ per ton (according to local market), 0.65% monthly return rate and 10% annual interest rate.

2.3 Restriction to Model Applicability

NeStRes model was idealized as a tool to support the decision on how to operate non-strategic reservoirs for irrigation in water scarce environments. Hence, it is inappropriate to define operation criteria for strategic reservoirs with multiple water uses, especially if it includes human supply, for which high reliability level is required.

In the Brazilian semiarid, where the model was applied in this work, strategic reservoirs are operated by the water management agencies with 90% reliability level to guarantee that priority demands, like human supply, are not compromised during the frequent droughts (de Araújo et al. 2018). However, small reservoirs are unable to provide such high reliability level because most of them fall completely dry at least once every other year, as a consequence of the high evaporation rates.

To define which reservoirs can be operated based on NeStRes, the “Regulation Triangle Diagram” – RTD proposed by Campos (2010) was used in this study. RTD is a graphical method based on two reservoir efficiency factors (Eqs. 14 and 15) to estimate the percentages of water evaporation, spillage and possible withdrawal from reservoirs for 90% reliability level.

$$f_V = V_{\max}/\mu \quad (14)$$

$$f_E = \left(3K^{1/3}E\right)/\mu^{1/3} \quad (15)$$

Where: f_V and f_E are the dimensionless capacity factor and evaporation factor, respectively; V_{max} is the reservoir’s storage capacity (m^3); μ is the average annual inflow (m^3); E is the average evaporation (m^3) during the dry season; K is the reservoir aperture factor, which can be estimated by $K = V_{\max}/h^3_{\max}$; h_{max} is the maximum water depth in the lake (m).

By defining f_V and f_E, it is possible to estimate from the regulation triangle diagram the percentage of annual inflow that can be converted into water yield. In the study area, water yield from reservoirs is very sensitive to evaporation (Campos et al. 2016), and thus to the evaporation factor f_E.

The criterion to define the NeStRes model applicability was based on the reservoir efficiency, setting a restriction to structures that can convert at least 5% of the annual inflow into water yield. This limit stablishes that all reservoirs with $f_E < 0.65$ are able to supply water with high reliability (90%, according to Campos 2010), being appropriate for human supply and therefore unsuitable to be operated based on the NeStRes model. This criterion aims to avoid competition among human supply and irrigation from non-strategic reservoirs.

3 Results and Discussion

3.1 Model Application

Simulation of the 91 non-strategic reservoirs in the Banabuiú River Basin indicated that the maximum income obtained from the cultivation of maize is attained when the reservoirs are operated with reliability level of daily water supply in the range of 32% to 66% (Fig. 3), i.e. falling dry in roughly one to two thirds of the time.

This finding highlights the major role played by the climate in defining the operation criterion of small reservoirs in dry environments. For instance, Ouyang et al. (2018) simulated the irrigation of maize, cotton and soybeans from a pond (1×10^5 m^3 capacity) in East Mississipi, USA, where annual rainfall and evapotranspiration are 1300 and 600 mm, respectively. The authors found that the pond level would be drawn to near zero at a maximum of two times in 10 years. On the other hand, Sanfo et al. (2017) stated that a 3×10^5 m^3 capacity reservoir in Burkina Faso is able to irrigate a variable area in the range of 17 to 25 ha and that dry season production is not always possible because the reservoir is not completely filled every year, suggesting that farm ponds are used for supplemental irrigation. In that region, annual rainfall is approximately 850 mm and temperature ranges roughly from 20 °C to 38 °C, similar to the BRB.

The results in the study basin suggest a paradigm change respecting the use of water from small reservoirs for irrigation: to switch the common practice of saving water by using it more intensely for crop production and saving the agriculture revenue, which is not susceptible to evaporation loss as in the previous practice (Fig. 2).

Seventy six percent of the simulated reservoirs presented optimum operation with reliability level of daily water supply in the range of 40% to 55%. From the curves of dimensionless income versus the reliability level for all 91 studied reservoirs, illustrated in Fig. 3, one can depict that operating any of the reservoirs with 54% reliability level leads to, at least, 85% of the maximum possible income from irrigated maize.

The optimal criterion occurring in a narrow range of reliability levels for the entire BRB indicates that the NeStRes model can be used to define general operation rules of non-strategic reservoirs at the basin scale. This is particularly important in data scarce regions such as the Brazilian semiarid (Zhang et al. 2016; Pereira et al. 2019), where simulation of individual reservoirs may be prevented by the lack of data.

Operation of the small reservoirs with 90% reliability level – the same criteria adopted for the strategic reservoirs used for human supply – lead to high inefficiency in the water use: adopting the current practice of saving water, irrigated farming of maize crop produces income in the range of 0.35 to 0.80 of the maximum possible income.

De Araújo and Bronstert (2016) studied drought propagation in the Jaguaribe Basin, inside which the BRB is located, by assessing the temporal dynamics of various sized structures: large, middle-sized and small reservoirs, wells and cisterns. The authors found that small reservoirs are the least effective structures, being unable to cope with long-term droughts. In their study about scale issues in the governance of water, van der Zaag and Gupta (2008) had already discussed on the role of small reservoirs in the hydrologic system, highlighting the importance of such structures for livelihood even though large reservoirs are more hydrologically- and costly-efficient.

The optimal reliability level of daily supply for irrigation purposes shows some correlation (Pearson R = 0.59) with the capacity factor (f_V) (Fig. 4). Representing the residence time of the

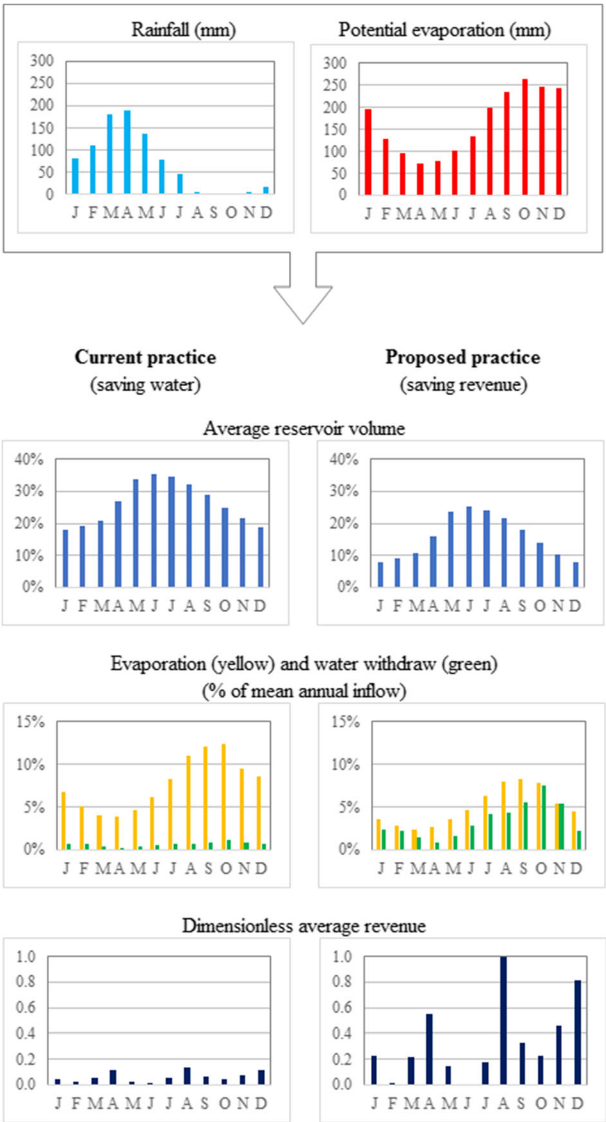

Fig. 2 Current and proposed practices of water use from non-strategic reservoirs for irrigation

water in the reservoir (τ), the capacity factor captures information not only on the potential volume of water that can be used for irrigation, but also on the hydrological regime. Other reservoir characteristics, such as the trophic level, are correlated to the capacity factor (Wiegand et al. 2016), which can be estimated with limited data and, therefore, represents a good parameter for the management of small non-strategic reservoirs in the absence of more detailed data.

The simulations performed with the NeStRes model in the semiarid Banabuiú River Basin brings insights about the role of such structures in the hydrologic system. Pereira et al. (2019) report that the Water Resources Management Company of the State of Ceará, where the BRB

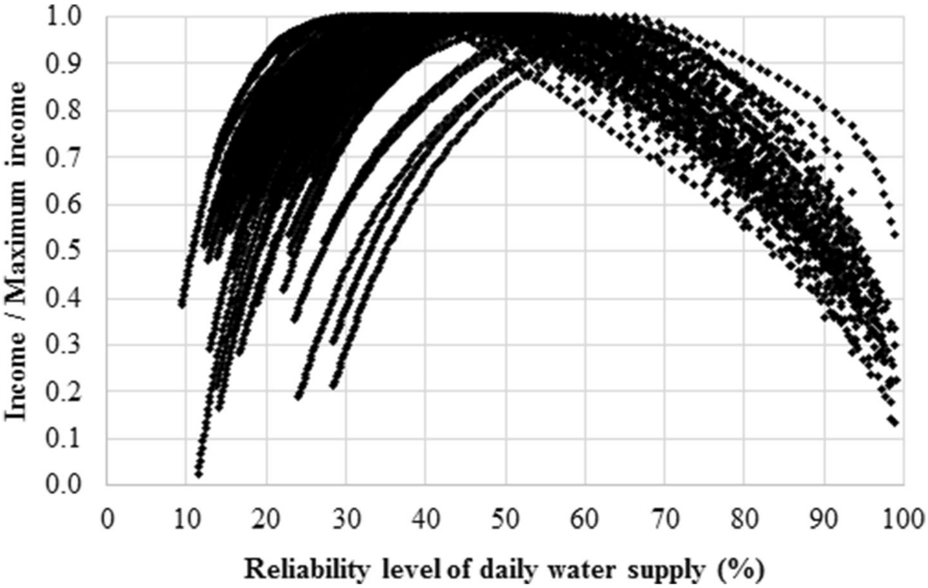

Fig. 3 Ratio of the income to the maximum possible income from irrigated maize crop according to the reliability level of daily water supply

is located, monitors 155 strategic reservoirs, whereas the global water mapping performed by Pekel et al. (2016) indicates the existence of over 20,000 reservoirs in the same area of 149,000 km^2. Although representing approximately 90% of the total storage capacity (Gutiérrez et al. 2014), the strategic reservoirs promote a very centralized water availability, with the water spatial distribution being met by the smaller ones. A more rational use of the non-strategic reservoirs helps meeting their role in livelihood and income generation in the rural areas.

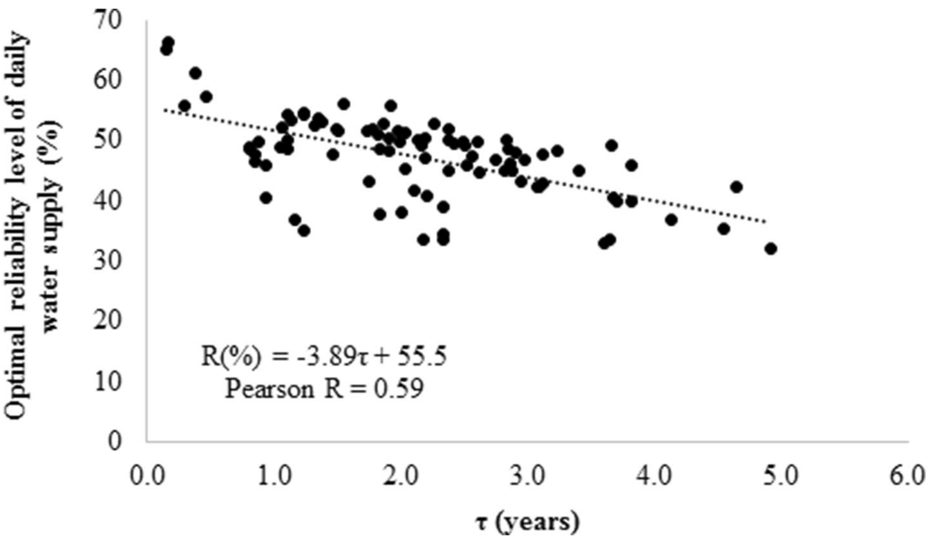

Fig. 4 Optimal reliability level of daily water supply versus the residence time of the water in reservoirs

Furthermore, the use of non-strategic reservoirs for irrigation alleviates the demand on the strategic ones, that serve multiple uses including human supply. In high-density reservoir networks, it is likely that definition of distinct reservoirs for different water demand sectors may reduce conflicts, like the ones observed in the semiarid Brazilian region after a 6 years-duration drought (2012–2017) (de Araújo et al. 2018).

At last, Di Baldassarre et al. (2018) argue that water availability enhancement through the construction of reservoirs tends to increase the water demand as well, a feedback named as “reservoir effect”. Therefore, water supply dependence on few sources may lead to higher vulnerability and more intense damages during droughts. Kuil et al. (2016) simulated the temporal dynamics of water availability and how the Mayas reacted to it, indicating the reservoir effect as a possible cause of the civilization collapse. In the State of Ceará, Brazil, de Araújo and Bronstert (2016) assessed hydrological droughts and their effects on society, concluding that decentralized water supply with multiple-sizes structures tend to reduce the vulnerability of hydrological systems to droughts. In that sense, use of non-strategic reservoirs for irrigation also contributes to increase the system resilience by decentralizing water supply for multiple uses.

The sensitivity analysis indicated that the income resulting from the irrigation of maize crops in the study area (Fig. 5a) is highly impacted by variations in the climatic and agricultural factors, as well as the sale price of the corn. Precipitation increase or evaporation decrease by 50%, can raise the income by over 100% and roughly 50%, respectively. The income is also very sensitive to the sale price of the corn, which plays a major role in the model outcome, and the crop cycle and water demand, particularly for negative variations of these factors which significantly increase the income. However, the results are insensitive to the interest and return rates of the economic module in the range of the simulations. The intense water use from reservoirs ensures yearly productions, avoiding that negative economic balances last too long and, thus, reducing the impact of the interest rate. On the other hand, the dry periods prevent too frequent harvests, and the positive economic balances are also limited in time.

The reliability of daily water supply is more stable and less impacted by variations in the climatic, agricultural and economic factors (Fig. 5b). Still, reductions of precipitation and crop cycle by 50% can diminish the reliability level by approximately 70%, whereas a decrease of the crop sale price by 50% can increase the optimum reliability of water supply by 100%.

Despite the potential of NeStRes model demonstrated in this work, we are still unable to capture how the farmers’ feedback to the new agricultural system would require changes to the proposed reservoirs’ operation, considering the coupled human-water system (Sivapalan et al. 2012). For instance, Pande and Savenije (2016) developed a sociohydrological model for smallholder farmers in Maharashtra, India, and assessed the adaptation strategies by farmers under unfavorable hydrological and/or economic circumstances. Roobavannan et al. (2017) used the Murrumbidgee River Basin case study, in Australia, to demonstrate how the economy diversification changed society’s values and promoted a transition of water allocation towards a more sustainable agriculture.

Some important features to be considered in future works about the co-evolution of society and the water fluxes are:

– What is the impact on the inflow to strategic reservoirs promoted by a more intense water use from small upstream reservoirs? How society reacts to possible lower storage in the strategic structures used for human supply?

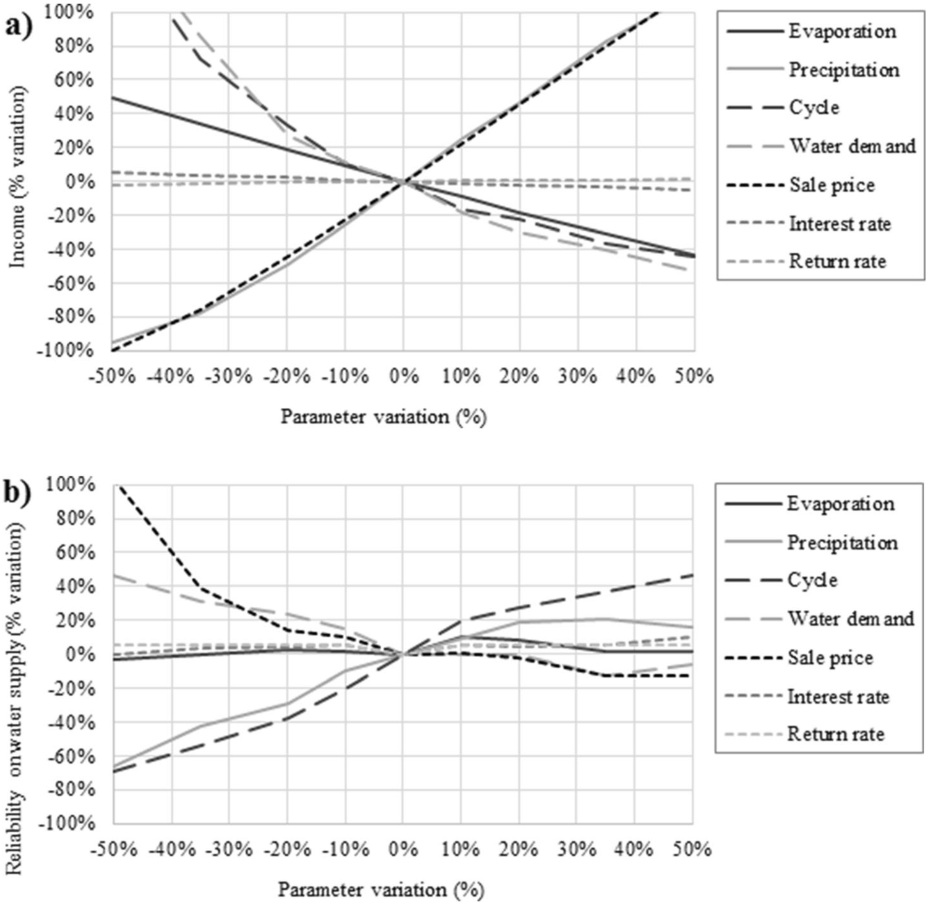

Fig. 5 Impact of the NeStRes climatic, agricultural and economic factors on the **a** income and **b** optimum reliability of daily water supply

- If intense irrigation is practiced in the region based on the proposed criteria, how can high availability of a product reduce the market price and impact farmers' decisions?
- How resilient are farmers to hold high debts during long-term droughts, when irrigated crop production is very restricted from small reservoirs?

3.2 Restriction to Model Applicability

The criterion defined as restriction for the applicability of the NeStRes model ($f_E < 0.65$) was tested for 134 strategic reservoirs monitored by the Water Resources Management Company of Ceará (COGERH) in the Federal State of Ceará, where the Banabuiú River Basin is located. Those reservoirs were expected to fall out the limit for model applicability, as they serve important water demand centers, including human supply, and therefore cannot be operated with focus on irrigation only. Indeed, all the strategic reservoirs monitored by COGERH presented $f_E < 0.65$ (Fig. 6) and were classified as unsuitable to be operated with the NeStRes model, validating the adopted criterion.

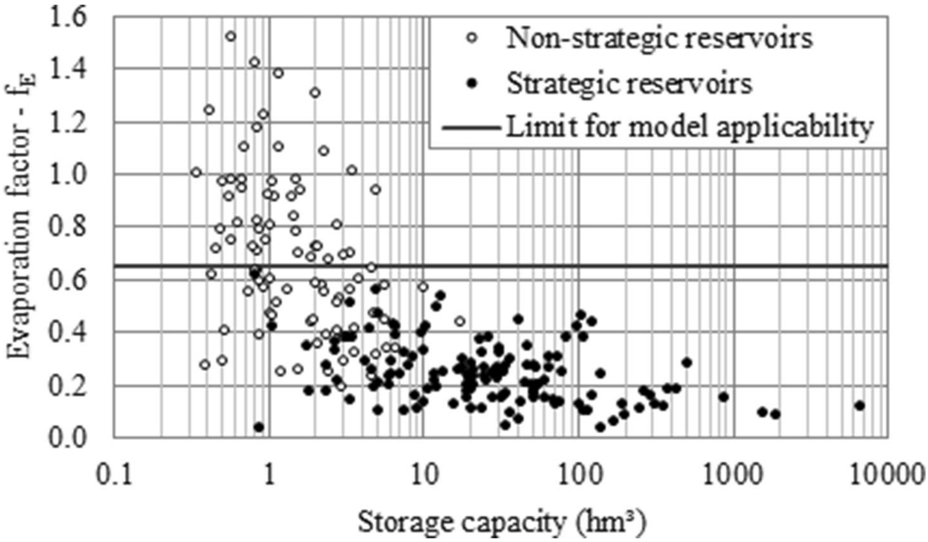

Fig. 6 Restriction to the NeStRes model applicability

The 91 studied non-strategic reservoirs presented a wide range of f_E from 0.2 to 1.5, with 48% classified as suitable for the NeStRes model (Fig. 6). The remaining 52% of the reservoirs, which can supply some water with high reliability and present restriction to be operated with the model, are small reservoirs ($< 10 \times 10^6$ m^3) not managed by the public sector. In such cases, operation of the reservoir must be based on the main demands to be supplied and the NeStRes model is recommended only if no competition exists among irrigation and the human and cattle priority uses, as defined by the Brazilian legislation (Brazil 1997).

4 Conclusions

Human water supply in drylands is usually accomplished by water storage in strategic surface reservoirs operated with high reliability level to avoid supply failure. However, this practice is inefficient for small reservoirs unable to yield water for long periods, under high evaporation rates, without complete drying. Therefore, the NeStRes model is proposed for the operation of small non-strategic reservoirs for irrigation purposes in drylands, with the paradigm change of using the water for crop production and saving the revenue, instead of saving water, susceptible to evaporation loss.

Simulation of 91 reservoirs in the semiarid Banabuiú River Basin indicated that the maximum income obtained with the irrigation of maize is achieved when the reservoirs are operated with reliability levels of daily water supply in the range of 32% to 66%, thus falling dry in roughly one to two thirds of the time. Reservoirs' operation with a fixed reliability level of daily water supply of 54% produces at least 85% of the maximum possible income for all simulated reservoirs.

The optimal reliability level of daily supply for irrigation purposes shows some correlation with the residence time of the water in the reservoirs (Pearson $R = 0.59$). Therefore, water residence time may be used to define the criterion for operation of small reservoirs for irrigation in data scarce regions.

Important insight may be drawn from the application of the NeStRes model about the role played by different reservoirs in the water system: whereas the common practice of "saving water" is desired for strategic reservoirs, reducing the risk of human water supply failure, non-strategic reservoirs can be more intensely explored to generate income from irrigated agriculture in drylands.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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