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# Simulation Model to Assess the Water Dynamics in Small Reservoirs

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**Abstract**

Small reservoirs play a key role in agricultural development in the Brazilian Savannah (Cerrado) region. They contribute to diminishing rural communities' vulnerability to drought and improve the livelihood of rural populations. Thousands of small reservoirs have been built in the last few decades in the Cerrado biome; however, efficient water management and sound planning are hindered by inadequate knowledge of their water dynamics. The main objective of this study was to develop a dynamic simulation model (SD) to assess the small reservoir (SR) water dynamics in the Brazilian Cerrado region. Daily data on reservoir inflows were obtained for the period from October 2009 to September 2011, and extended to June 2015 through modeling. The developed model was calibrated and validated with historical data. Sensitivity analysis was applied to assess the main variables that influence the SR water dynamics. The results indicated that reservoir inflow was the variable that had the highest impact on SR water volume, followed by the reservoir surface area and by evaporation and infiltration, which together represented 14.4% of reservoir inflow. Approximately 81.9% of the SR stored water was available to attend to the water demand. The related research findings of this study could be favorable for guiding the reservoir's construction (optimal size) and management of irrigation and human demand by evaluating different variables and fluxes. This study adopts basic approaches and equations to determine the relationships between variables with observed values and estimated fluxes in a small reservoir, which can be useful to simulate reservoir dynamics, adjust the initial values, or alternatively, simulate climate change scenarios.

**Keywords** System dynamic · Sensitivity analysis · Evaporation · Water resources · Reservoir water budget

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## 1 Introduction

Sustainable management of water resources is crucial to promoting high-quality development and ensuring a region's water security (Sun et al. 2017; Wang et al. 2020). The sustainable management of water in agriculture is a challenge, mainly in regions with higher water deficits, to maintain water consumption for irrigation and food production (King et al. 2020). This challenge has greatly increased the need to understand and predict the water resource systems dynamic and their impact on beneficiaries (Zomorodian et al. 2018) as well as predict the future water availability (Zeng et al. 2021). The scarcity of water supply in agriculture is mainly caused by climate changes and land use changes, such as extreme drought and water deficit, and degradation by the intensification of agriculture (Citakoglu and Coşkun 2022). Thus, the risks from water utilization are even greater with the intensification of irrigated agriculture and negative effects of climate change, mainly with an increase in temperature and drought (Olmo and Bettolli 2022; Zhang et al. 2022) prolonging the dry season (Pires et al. 2016) and consequently reducing the flow available in water sources (Mirauda et al. 2020).

As an important sustainable water management, reservoir regulation plays a crucial role in the insurance of water resources supply and demand balance, especially during drought seasons (Xu et al. 2019; Zhang et al. 2022). Small reservoirs are an alternative for the sustainable and efficient management of water resources and increase water availability in hydrographic basins (Althoff et al. 2019; 2020). Small reservoirs can contribute to reducing the vulnerability of rural communities to drought, improving the livelihoods of rural populations (Austin et al. 2020). In addition small reservoirs temporarily store excess rainwater, which can play an important role in regulating downstream flows and can provide protection against flooding (El Gayar 2020). Furthermore, these rural infrastructures can have positive impacts on underground aquifers, thus increasing baseflow in the downstream section of the catchment (Habets et al. 2018; Kourakos et al. 2019).

However, most problems with dimensioning small reservoirs are because of the lack of detailed information about the hydraulic structures compare to large reservoirs (Kalogeropoulos et al. 2020; Fabre et al. 2015), making it difficult to include small reservoirs in hydrodynamic models (Collischonn et al. 2011). Despite that, the impact of a single small reservoir on the hydrological behavior of a drainage basin may not be significant (Habets et al. 2018; Rabelo et al. 2021), their impact on water systems needs to be better quantified to the decision-making basis for the development of regional water resources management strategies (Rodrigues et al. 2012; Zhang et al. 2022).

Mathematical models developed to simulate the hydrological dynamic of drainage basins where there are small isolated or cascading reservoirs are essential for planning and managing water resources (Nathan and Lowe 2012; Kim et al. 2021). The results of these models are important for water resource agencies as they can support water resource planning, especially when making long-term forecasts (Al-Jawad et al. 2019; Jing et al. 2022), thereby helping to develop strategies to improve usage and efficiency in decision-making, seeking to ensure the sustainable use of water resources. The results from the dynamic system models are also important to assist in developing water policies with programs and projects to support the storage infrastructure (Sun et al. 2017; Xu et al. 2019; Zhang et al. 2022). However, dynamic systems models to assess water supply and demand in small reservoirs as a tool for the management and conservation of water resources, are still limited.

In this context, an increase in water scarcity has been observed in the Cerrado region attributed to long periods of drought, rapid economic development, and inefficiency in the management of water resources (Althoff et al. 2019, 2020). The Cerrado region concentrates about 64% of Brazil's irrigated area (ANA 2021), and approximately 80% of all center pivots in the country (Althoff and Rodrigues 2019). Despite the strategic importance of the development of a region, the environmental impacts, mainly caused by poorly sized reservoirs, have made it difficult to build new reservoirs in several regions of Brazil, especially in the Cerrado. Therefore, it is increasingly important to generate information to support the allocation and construction of new reservoirs in the Brazilian Cerrado region. Thus, the aim of this study was to evaluate the water availability and demand dynamic of a small reservoir over time in a rural community in the Brazilian Cerrado region.

# 2 Material and Methods

## 2.1 Study Area Description

The study was carried out in a small reservoir named R2, (Fig. 1D), located in the Brazilian Cerrado region It lies between latitude 15° 91′ 26″ S and longitude 47° 40′ 91″ W.

The reservoir has an area of approximately 0.25 ha, with a total storage capacity of approximately 3317.1 m$^3$ and a maximum depth of the dam crest of 3.40 m (Rodrigues and Schuler 2016). The reservoir is mainly used for irrigation and domestic purposes. The main morphometric characteristics of the small reservoir and its watershed are presented in Table1.

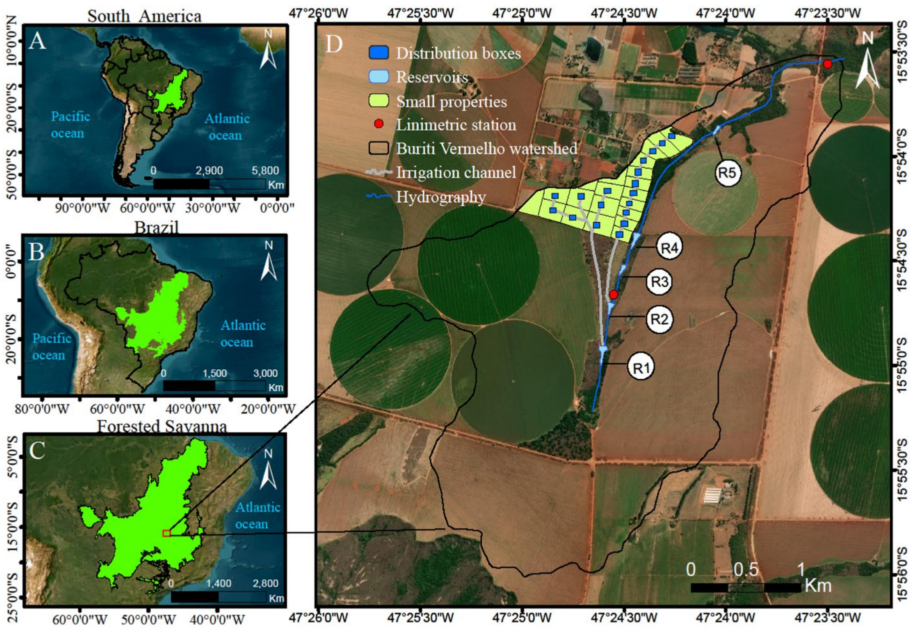


**Fig. 1** Buriti Vermelho river watershed (D) with emphasis on the small reservoirs arranged in a cascade (R1, R2, R3, R4 and R5), and the hydrological monitoring system

**Table 1** Morphometric characteristics of the small reservoir and its drainage basin

| Characteristics | Values |
|---|---|
| Drainage area | 10.3 $Km^2$ |
| Perimeter | 15.74 km |
| Main channel length | 4.23 km |
| Average elevation | 915 m |
| Equivalent slope | 0.0302 m $m^{-1}$ |
| Shape factor | 0.51 |
| Compactness coefficient | 1.17 |
| Drainage density | 0.43 km $Km^{-2}$ |
| Order | 1 |
| Concentration time | 22.48 min |
| Main river slope | 0.169 m $km^{-1}$ |
| Total dam capacity | 3317.1 $m^3$ |
| Dam surface area | 0.25 ha |
| Length of the dam wall | 3.40 m |
| Dam length | 85 m |

The reservoir is located in the Buriti Vermelho watershed (BVRDB). The basin has a drainage area equal to 10.3 $km^2$, and is located between the geographic coordinates of latitude 15° 55′ 56″ S and longitude 47° 23′ 53″ W. The Buriti Vermelho River is its main river and is a tributary of the Estreito River which flows into the Preto River, which in turn flows through the Paracatu River to the São Francisco River, which is an important water source for the Brazilian semi-arid region (Wendt et al. 2015).

The climate of the region is tropical (Aw) with a humid and dry climate according to the Köppen classification. The local climatic condition is characterized by a single rainy season from October to April, with peak rainfall measured in January, and a dry season from May to September. Com relação á população, the watershed is composed of farmers with property areas ranging between 1.200 hectares (Castro et al. 2009). About eleven farmers, with a total area of 23 ha, withdraw water from the reservoir (R2).

## 2.2 Hydrological Monitoring and Irrigation Channel

The hydrological variables such as inflow and the water level of the reservoir were measured with devices installed by the Brazilian Agricultural Research Corporation (Embrapa Cerrados) (Rodrigues and Schuler 2016). The inflow to the reservoir was monitored at two locations in the basin through two linimetric stations connected with dataloggers programmed to store flow values every five minutes. One of the linimeters was installed downstream of the reservoir (R2) and the other at the Basin outlet (Fig. 1D).

The water level variation was monitored in the R2 and R5 reservoirs through linimeters connected to dataloggers programmed to record the water level variation in the reservoirs at five-minute intervals (Rodrigues and Schuler 2016).

The irrigation channel receives water from the second reservoir through a long tube, whose flow is controlled by varying the water height (hydraulic head) in the reservoir. The irrigation channel has a free flow with a circular shape coated with concrete, 665 m long, 0.30 m in diameter, average slope of 0.0034 m $m^{-1}$ and the difference in level from the community to the reservoir is approximately 3.31 m.

### 2.3 Development of the System Dynamics Model

The mathematical model to simulate the water dynamics in the small reservoir was developed using the Vensim-PLE® software (Ventana Systems 2013), which enables building dynamic simulation models including equations that represent changes as a function of time.

The developed model has the following assumptions: (i) the water infiltration into the soil is uniform in the reservoir bed, with the area considered for infiltration equivalent to 65% of the water surface; (ii) the evaporation rate occurs uniformly and over the entire of the water surface; (iii) the infiltrated water does not return to the water system; (iv) the amount precipitated on the reservoir water surface is neglected; and (v) capillary rise is neglected.

The inflow to the reservoir is computed on a daily basis. The water dynamics in the reservoir was simulated at intervals of five minutes; to do so, the values of the influent flow, evaporation and infiltration variables were discretized in a time of five minutes. Figure 2 illustrated the framework of the SD model considering the water dynamics and the demand.

### 2.4 Model Equations

#### 2.4.1 Water Balance of a Small Reservoir

The water balance of the reservoir in a given period of time was calculated by Eq. (1). Where the difference between total water inflow and outflow is equal to the change in water storage in the reservoir over time (Habets et al. 2018).

$$V(t) = V(to) + \int_{to}^{t} [Q_A(t) - Q_{EV}(t) - Q_I(t) - Q_{SF}(t) - Qsv(t)] \quad (1)$$

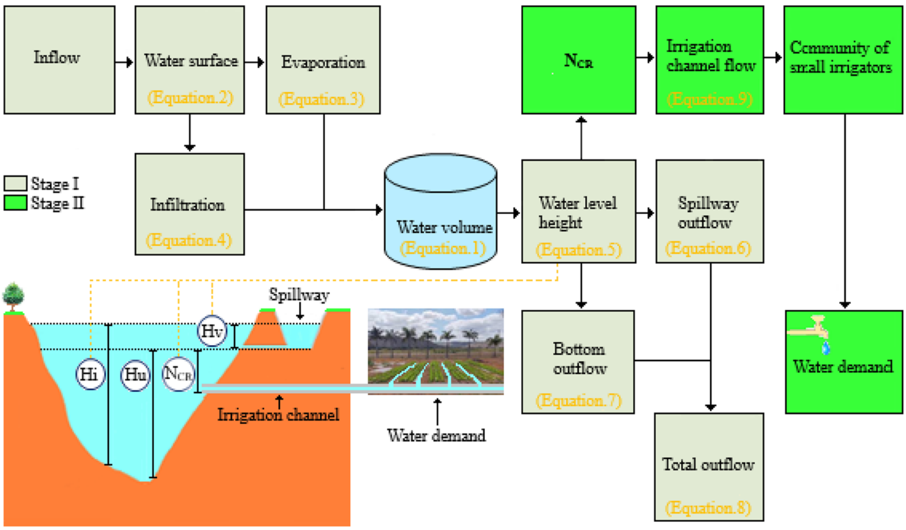


**Fig. 2** Representative flowchart of the dynamic simulation model ($N_{CR}$ = water level connecting the reservoir to the irrigation channel, (m); $H_V$ = water height at the spillway, (m); $H_i$ = water level height in the time i, (m); $H_u$ = useful height, (m))

where: V (t) = volume of water in time t; V (to) = volume of water in time to; $Q_A$ t = inflow in time t; $Q_{EV}$ (t) = evaporation in time t; $Q_I$ (t) = infiltration in time t; $Q_{SF}$ (t) = bottom outflow in time t; $Q_{SV}$ (t) = spillway outflow in time t.

### 2.4.2 Water Surface

With the inflow data to the reservoir for each time interval of 5 min, the current reservoir surface area was calculated by Eq. (2). It was defined base on deep-area-volume of small reservoirs in the Cerrado from Brazil and Gana (Rodrigues and Liebe 2013).

$$W_{SA} = \propto_1 \left(tQ_A\right)^{K_1} \tag{2}$$

where: $W_{SA}$ = water surface area, (ha); t = time interval, s, (t = 300); $Q_A$ = inflow, $m^3\ s^{-1}$; $\alpha_1$ and $K_1$ = coefficients, dimensionless.

The $\propto_1$and $k_1$ coefficients were considered with values equal to 1.09 and 0.000513 respectively, established based on volume, area and depth relationships, adjusted for small reservoirs located in the Brazilian Cerrado (Rodrigues and Liebe 2013).

### 2.4.3 Evaporation

Once the reservoir surface area was calculated, the evaporation was calculated as Eq. (3), obtained by estimating evaporation including climate variables in a class A tank (Althoff et al. 2019).

$$Q_{EV} = 0.0034722\left(0.924 + 0.057T_X\right)W_{SA} \tag{3}$$

where: $Q_{EV}$ = evaporation, ($m^3\ s^{-1}$); $T_x$ = maximum temperature, (°C).

### 2.4.4 Infiltration

The infiltration rate was uniform, meaning that the spatial variability of soil characteristics which interfere with infiltration was neglected. The water surface area is always greater than the area at the bottom of the reservoir where most of the infiltration occurs. Therefore a trapezoidal-shaped reservoir was considered in order not to overestimate the infiltrated volume (Pinhati et al. 2020). Thus, for the purposes of calculating infiltration, the water surface area was divided by two, calculated by Eq. (4).

$$Q_I = \frac{\left(\frac{I_{mn}\left(W_{SA}\frac{10{,}000}{2}\right)}{1{,}000}\right)}{t} \tag{4}$$

where: $Q_I$ = infiltration, ($m^3\ s^{-1}$); $I_{mn}$ = mean infiltration, (mm $day^{-1}$).

An average infiltration rate of 5.0 mm $day^{-1}$ was considered based on research carried out in small reservoirs in the Brazilian Cerrado region (Rodrigues and Dekker 2008).

### 2.4.5 Water Level Height

The current stored water volume was calculated as a function of the infiltrated and evaporated volumes. With the current stored volume, the water height in the reservoir in the time i was calculated by Eq. (5).

$$\log\left(H_i\right) = \frac{\log\left(\frac{Vcurr}{k}\right)}{\propto} \tag{5}$$

where: $H_i$ = water level height in the time i, (m); Vcurr= current stored water volume; α, k = coefficients related to the shape of the reservoir, dimensionless.

The values of ∝ and k coefficients were equal to 2.74 and 114.58 respectively, established based on volume, area and depth relationships, and adjusted for small reservoirs located in the Brazilian Cerrado region (Rodrigues and Liebe 2013).

### 2.4.6 Spillway Outflow

The spillway flow was calculated with the current water level in the reservoir. Whenever $H_i$ is greater than the useful height $H_u$, there will be flow in the spillway (Fig. 2). A trapezoidal-shaped spillway was assumed in the flow calculation Eq. (6). The physical characteristics of the spillways of the reservoirs were obtained from the Embrapa Cerrados data base (Rodrigues and Schuler 2016).

$$Qsv = 1.86LH_v{}^{1.5} \tag{6}$$

where: $Q_{SV}$ = spillway outflow, ($m^3\ s^{-1}$); L = spillway width, (m).

### 2.4.7 Bottom Outflow

With this information and knowing the cross-sectional area of the bottom outlet tube, the bottom outflow rate of the reservoir was calculated by Eq. (7) (Drumond et al. 2014).

$$Q_{SF} = AC_V\sqrt{2gH_i} \tag{7}$$

where: $Q_{SF}$ = bottom outflow, $m^3\ s^{-1}$; A = tube cross-sectional area, $m^2$; g = gravity acceleration, $m\ s^{-2}$; Cv = speed correction coefficient (0.82).

### 2.4.8 Total Outflow

The water dynamics were simulated through the water balance in the reservoir, calculated by Eq. (8). The variable of interest is the reservoir total outflow that contributed to downstream.

$$Q_S = Q_{SF} + Q_{SV} \tag{8}$$

where: $Q_S$ is the reservoir total outflow, $m^3\ s^{-1}$.

### 2.5 Risk Assessment of Not Meeting the Expected Water Demand

Adjustments and adaptations were additionally made to the SD model, including new state, auxiliary and flow variables in order to assess the risk of not meeting the water demand ($D_H$) forecast in an irrigation project that serves an agricultural community of small irrigators.

Next, the series of flows was extended from October 2009 to June 2015 using the GR5J model to assess the risk of not meeting the forecasted water demand (Le moine 2008). The GR5J model was executed using the airGR package (Coron et al. 2017) in the R software (R Development Core Team 2018).

The water demand of the irrigation project was estimated using the Simulation Model for Irrigation Strategies (MSEI) (Alves et al. 2019). Based on this information, the outflow in the irrigation channel was calculated using the Manning equation Eq. (9) (Dey 2003).

$$Q_{ABS} = \frac{1}{n} ARh^{\frac{2}{3}} I^{\frac{1}{2}} \tag{9}$$

where: $Q_{ABS}$ = irrigation channel flow, ($m^3\ s^{-1}$); n = roughness coefficient, ($s^{-1}\ m^{-\frac{1}{3}}$); A = cross-sectional area to flow, ($m^2$); Rh = hydraulic radius, (m); I = mean slope, ($m\ m^{-1}$).

### 2.6 System Dynamics Model

The model description of the small reservoir using the Vensim@ program was based on previous studies (e.g., Wu et al. 2013; Sun et al. 2017; Rodrigues et al. 2021; Luo et al. 2009). This model presents three types of variables: state variable is the water volume of reservoir, flow variable is represented by differential equations (ex. Inflow and outflow), and auxiliary variables are those that influence system flows (Fig. 3).

### 2.7 Evaluation and Calibration of the System Dynamics Model

Water level variation data observed in the R2 reservoir were used to evaluate the SD model, disregarding the withdrawals. To do so, a sample was divided into three periods (Althoff and Rodrigues 2021). The first 3 months were used for warming-up the model, 14 months for calibration and the last 7 months for validation.The SD model performance was evaluated using statistical metrics to compare the simulated and observed values of the test set for the calibration and validation.

The statistical metrics adopted and used were the mean absolute relative error (MARE), Eq. (10), mean absolute error (MAE), Eq. (11) (Abro et al. 2020), root mean square error (RMSE), Eq. (12), coefficient of determination ($R^2$), Eq. (13), Nash–Sutcliffe Efficiency Index (NSE), Eq. (14) (Nash and Sutcliffe 1970) and Kling-Gupta efficiency index (KGE), Eq. (15) (Gupta et al. 2009). All statistical metrics were performed using the R software (R Development Core Team 2018).

$$MARE = \frac{1}{m} \sum_{i=1}^{m} \frac{\left|(Sim_i - Obs_i)\right|}{Obs_i} \tag{10}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left|Sim_i - Obs_i\right| \tag{11}$$

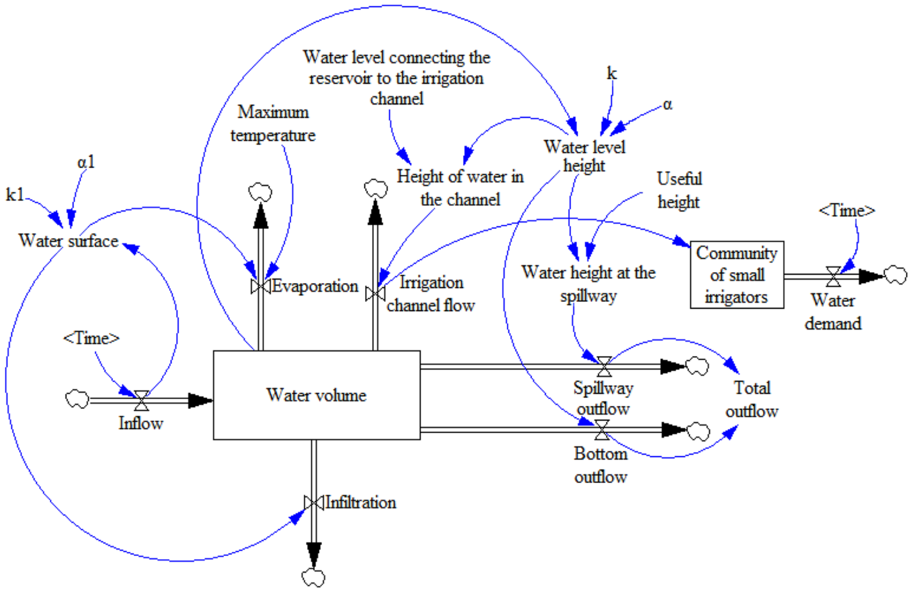


**Fig. 3** Causal loop diagram of the system dynamic model to evaluate water dynamics and the contribution of small reservoirs to gains in water availability and demand fulfillment. (∝; k; ∝1; k1 = dimensionless coefficients)

$$\mathrm{RMSE} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(\mathrm{Sim}_i - \mathrm{Obs}_i)^2} \tag{12}$$

$$R^2 = \frac{\sum_{i=1}^{n}\left(\mathrm{Obs}_i - \overline{\mathrm{Obs}_i}\right).\left(\mathrm{Sim}_i - \overline{\mathrm{Sim}_i}\right)}{\sqrt{\sum_{i=1}^{n}(\mathrm{Obs}_i - \overline{\mathrm{Obs}_i})^2}.\sqrt{\sum_{i=1}^{n}(\mathrm{Sim}_i - \overline{\mathrm{Sim}_i})^2}} \tag{13}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{QObs}_i - \mathrm{Osimi})^2}{\sum_{i=1}^{n}(\mathrm{OObs}_i - \mathrm{Qmeani})^2} \tag{14}$$

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{15}$$

where:

$$r = \frac{\sum_{i=1}^{n}\left(\mathrm{Obs}_i - \bar{\mathrm{O}}\mathrm{bs}_i\right)}{\sqrt{\sum_{i=1}^{n}(\mathrm{Obs}_i - \bar{\mathrm{O}}\mathrm{bs}_i)}.\sqrt{\sum_{i=1}^{n}\left(\mathrm{Sim}_i - \bar{\mathrm{S}}\mathrm{im}_i\right)}}$$

$$\beta = \frac{\mu_s}{\mu_o}$$

$$\gamma = \frac{CV_s}{CV_o} = \frac{\sigma_s / \mu_s}{\sigma_o / \mu_o}$$

In which: n = number of observations; μs and μo = arithmetic mean of simulated and observed data; σs and σo = standard deviation of simulated data from observed values; Cvs and Cvo = coefficient of variation of simulated and observed data; Oi and Si = observed and simulated data values (SPPs) on day i; $\bar{O}$ and $\overline{S}$ = arithmetic mean of observed data and simulated data (SPPs), respectively.

### 2.8 Evaluation of the Behavior of the Main Variables that Influence the Water Dynamics in Small Reservoirs

A sensitivity analysis was performed at this stage considering the main variables of the SD model. The reservoir volume was selected as the target variable in the sensitivity analysis, and the values of the main variables of the SD model were varied, disregarding the withdrawals for water demand ($Q_A$, $Q_I$, $Q_{EV}$, $W_{SA}$, $Q_{SV}$, $Q_{SF}$, $H_i$ and $Q_S$). This means the values of these variables were automatically increased and decreased by ± 10% in relation to the base value for the period from September 2009 to October 2011.

## 3 Results

### 3.1 Calibration and Evaluation of the System Dynamics Model

A total of 90 days were used to warm-up the SD model (12.5% of data), 420 days for calibration (58.3% of data) and 210 days for validation (29.2% of data). Figure 4 shows the water level variation over time. It is observed in there was good adherence over time between the simulated and observed water level data.

The following indices were obtained during the warm-up period: $R^2 = 0.667$, MARE = 0.0026 and positive Pearson correlation equal to 0.811. The results obtained indicated a good performance of the SD model, which can be classified in the "very good" category (Mararakanye et al. 2020).

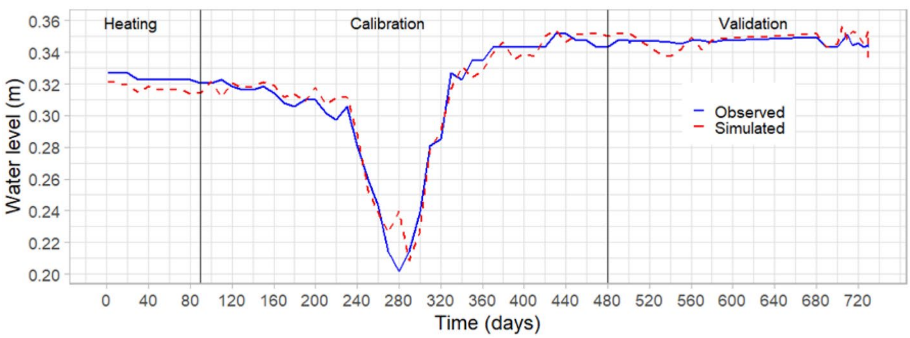


**Fig. 4** Observed and simulated water level for the warm-up period, calibration and validation of the system dynamic model

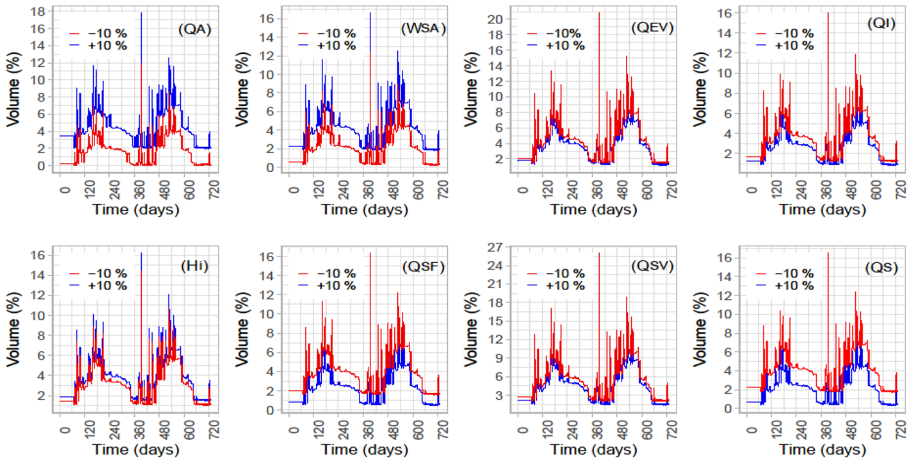

**Fig. 5** Variation in the reservoir volume (%) as a function of the variation of ± 10% in the value of $Q_A$, $W_{SA}$, $Q_{EV}$, $Q_I$, Hi, $Q_{SF}$, $Q_{SV}$ and $Q_S$ in the period from September 2009 to October 2011. ($Q_A$ = inflow; $W_{SA}$ = water surface; $Q_{EV}$ = evaporation; $Q_I$ = infiltration; Hi = water level height; $Q_{SF}$ = bottom outflow; $Q_{SV}$ = spillway flow; $Q_S$ = total outflow)

In addition, $R^2$ = 0.87, MARE = 0.00808 and positive Pearson correlation equal to 0.8972 were obtained in the calibration phase of the SD model. The SD model performance improved during the validation phase, with $R^2$ = 0.96, MARE = 0.00917 and positive Pearson correlation equal to 0.9613.

### 3.2 Sensitivity Analysis of the System Dynamics Model

The water volume stored in the reservoir was chosen as the target variable to assess the sensitivity of the SD model. Disregarding withdrawals, eight variables were selected for sensitivity analysis: $Q_A$, $Q_I$, $Q_{EV}$, $W_{SA}$, $Q_{SV}$, $Q_{SF}$, Hi, and $Q_S$ (Fig. 5 and Table 2).

The variation in the water volume stored in the small reservoir generally showed low sensitivity for variations in the Hi values and for variations in $Q_{EV}$ and $Q_{SV}$, meaning that the variations of these variables had little influence on the variation of the stored volume. On the other hand, the variation in the water volume stored in the reservoir was much more sensitive to the flow variables of $Q_A$, $Q_S$, $Q_{SF}$, $Q_I$ and $W_{SA}$.

**Table 2** Result of the sensitivity analysis of the dynamic system model applied to an isolated reservoir in the Buriti Vermelho River basin, DF, Brazil. (ΔVo = volume variation (%); $Q_A$ = inflow; $W_{SA}$ = water surface; $Q_{EV}$ = evaporation; $Q_I$ = infiltration; Hi = water level height; $Q_{SF}$ = bottom outflow; $Q_{SV}$ = spillway flow; $Q_S$ = total outflow)

| | $Q_A$ | | $W_{SA}$ | | $Q_{EV}$ | | $Q_I$ | |
|---|---|---|---|---|---|---|---|---|
| (%) | +10 | -10 | +10 | -10 | +10 | -10 | +10 | -10 |
| Δ Vo | 4.54 | 1.62 | 4.18 | 2.15 | 3.46 | 2.68 | 5.52 | 4.64 |

| | $H_i$ | | $Q_{SV}$ | | $Q_{SF}$ | | $Q_S$ | |
|---|---|---|---|---|---|---|---|---|
| (%) | +10 | -10 | +10 | -10 | +10 | -10 | +10 | -10 |
| Δ Vo | 3.75 | 3.13 | 4.30 | 3.75 | 3.88 | 2.39 | 3.98 | 2.16 |

**Table 3** Maximum, average and minimum values of flow and state variables in the isolated reservoir in the Buriti Vermelho River basin, DF, Brazil. (Vo = volume variation; $Q_A$ = inflow; $W_{SA}$ = water surface; $Q_{EV}$ = evaporation; $Q_I$ = infiltration; Hi = water level height; $Q_{SF}$ = bottom outflow; $Q_{SV}$ = spillway flow; $Q_S$ = total outflow)

| Variable | $Q_A$ | $Q_I$ | $Q_{EV}$ | Vo | $Q_{SF}$ | Qsv | Qs |
|---|---|---|---|---|---|---|---|
| **Unity** | ($m^3\ s^{-1}$) | ($m^3\ s^{-1}$) | ($m^3\ s^{-1}$) | ($m^3$) | ($m^3\ s^{-1}$) | ($m^3\ s^{-1}$) | ($m^3 s^{-1}$) |
| **Max** | 0.133 | 0.0101 | 0.00189 | 0.307 | 0.0721 | 0.0522 | 0.1243 |
| **Mean** | 0.035 | 0.0027 | 0.00052 | 0.065 | 0.0306 | 0.0025 | 0.0330 |
| **Min** | 0.024 | 0.0003 | 0.00011 | 0.007 | 0.0243 | 0.0007 | 0.0250 |

A variation of + 10% in the $Q_A$ value implied an average variation of 4.54% in the storage volume and a decrease of -10% implied an average variation of 1.62% (Table 3). A variation of + 10% in the $Q_S$, $Q_{SF}$, $Q_I$, $Q_{EV}$, $Q_{SV}$, Hi and $W_{SA}$ values caused an average change equal to 3.98%, 3.88%, 5.52%, 3.46%, 4.30%, 3.75% and 4.18%, respectively, in the variation of the volume stored in the reservoir.

A variation of -10% in the $Q_S$, $Q_{SF}$, $Q_I$, $Q_{EV}$, $Q_{SV}$, Hi and $W_{SA}$ values implied an average variation equal to 2.16%, 2.39%, 4.64%, 2.68%, 3.75%, 3.13% and 2.15% respectively, in the variation of the stored volume. The low sensitivity observed in relation to $Q_{SV}$ can be attributed to the fact that the spillway sheds water in a few periods of the year.

### 3.3 Simulation and Evaluation of Water Dynamics in the Reservoir

The simulation results of the behavior of the main input and output variables that impact the water dynamics in the reservoir are presented in Fig. 6. The maximum, average and minimum values of the $Q_A$, $Q_I$, $Q_{EV}$, $V_O$, $Q_{SF}$, Qsv and $Q_S$ variables for the reservoir evaluated in the Brazilian Cerrado region are presented in Table 3.

In analyzing the simulation results, it is observed that the $Q_A$ values (Fig. 6) ranged from 0.0248 $m^3\ s^{-1}$ to 0.133 $m^3\ s^{-1}$, with an average value equal to 0.0347 $m^3\ s^{-1}$. There was a decrease in $Q_A$ in two periods. The $Q_A$ in the first period, which was from march 30 to september 10, 2010, ranged from 180 to 340 $m^3\ s^{-1}$. The variation in the second period, which was from April 20 to September 29, 2011, was from 540 to 720 $m^3\ s^{-1}$. Rain does not occur in the region in these periods as a rule, which may be an explanation for the variation in $Q_A$ in these two periods. An average $Q_A$ decay of 0.00301 $m^3\ s^{-1}$ is observed during these periods. There is a great variability in the $Q_A$ values during the rainy season, with an average value of 0.00452 $m^3\ s^{-1}$.

$Q_A$ is the main inflow variable in the water balance in small reservoirs, and directly or indirectly influenced the behavior of all other variables, which followed the same trend of $Q_A$. It was observed that the $W_{SA}$ values (Fig. 6) ranged from 0.010 ha to 0.21 ha, with an average value equal to 0.048 ha. Moreover, $W_{SA}$ reduced an average of 0.051 ha $day^{-1}$ during the dry season. The $Q_I$ (Fig. 6) ranged from 0.0003 $m^3\ s^{-1}$ to 0.0101 $m^3\ s^{-1}$, with an average variation of 0.0027 $m^3\ s^{-1}$, and the $Q_{EV}$ ranged from 0.00011 $m^3\ s^{-1}$ to 0.00189 $m^3\ s^{-1}$, with an average of 0.00052 $m^3\ s^{-1}$.

The volume behavior (Fig. 6) presented low variation at the beginning of the simulation with an average of 0.0021 $m^3$, which can be explained by the uncertainties in the initial conditions of some flow, mainly the $Q_I$. The volume variation in the reservoir behaved similarly to the $W_{SA}$ during most of the simulation. The highest losses by $Q_I$

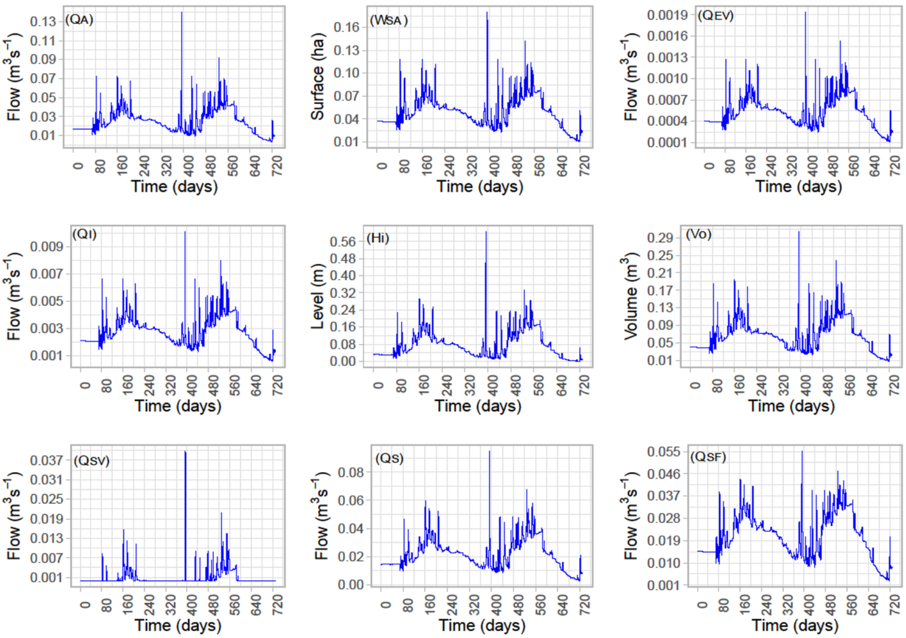


**Fig. 6** Simulation of the behavior of the main input and output variables that impact the water dynamics in the reservoir. (Vo = volume variation; $Q_A$ = inflow; $W_{SA}$ = water surface; $Q_{EV}$ = evaporation; $Q_I$ = infiltration; Hi = water level height; $Q_{SF}$ = bottom outflow; $Q_{SV}$ = spillway flow; $Q_S$ = total outflow)

and $Q_{EV}$ were observed on the days in which the highest $W_{SA}$ were recorded, with a greater variation in volume on those days ranging from 0.0077 $m^3$ to 0.307 $m^3$, with an average variation of 0.0655 $m^3$.

The Hi (Fig. 6) ranged from 0.01 m to 0.6 m, with an average variation equal to 0.077 m. The $Q_{SF}$ ranged from 0.0243 $m^3$ $s^{-1}$ to 0.0721 $m^3$ $s^{-1}$, with a mean value equal to 0.0321 $m^3$ $s^{-1}$; the maximum water level reached at the spillway ranged from 0.29 m to 0.6 m, with an average value of 0.42 m, generating a flow ranging from 0.00079 $m^3$ $s^{-1}$ to 0.0522 $m^3$ $s^{-1}$, with an average equal to 0.00251 $m^3$ $s^{-1}$, occurring at about 37.7% in time. The $Q_S$ ranged from 0.0251 $m^3$ $s^{-1}$ to 0.124 $m^3$ $s^{-1}$, with an average equal to 0.0330 $m^3$ $s^{-1}$.

After discounting the outputs by $Q_I$ and $Q_{EV}$, the results showed that the $Q_S$ ranged from 0.0251 $m^3$ $s^{-1}$ to 0.1243 $m^3$ $s^{-1}$, with an average equal to 0.0330 $m^3$ $s^{-1}$ (Table 3). Due to the outputs by $Q_I$ and $Q_{EV}$, it was verified there was a reduction of 4.8% in the average flow and an increase of 1.2% in the minimum flow due to the influence of the reservoir by increasing the water consumption by evaporation and recharging the water table by the infiltration in the dry season, which explains the reduction in the average flow and the increase in the minimum. In evaluating small reservoirs, Habets et al. (2018) observed a decrease in flow in global terms from 0.2% to 6.0% in the average flow and an increase of 44% in the minimum flow.

The results indicated that the higher the $W_{SA}$ values, the greater the $Q_I$ and $Q_{EV}$ losses. The $Q_I$ and $Q_{EV}$ losses are significant and impact the dam's water management. These water outflows from the reservoir caused a decrease in the volume of stored water and in the $Q_A$ of 14.4%, with 8.1% due to $Q_I$ and 6.3% due to $Q_{EV}$. In other words, a value equivalent to 6.582,1 $m^3$ of water which left the reservoir and that could be available for other uses. In this sense, minimizing $Q_{EV}$ and $Q_I$ losses is important to maintain the water security of the dam, especially during the dry season.

The largest $W_{SA}$ obtained during the simulation was equal to 0.201 ha, representing approximately 0.0021% of the total area of the Buriti Vermelho River basin. Since the evaporation is seen as a loss in the water system, it is important that installation places are defined in planning the construction of the reservoirs which allow the reservoir to store a large volume with a small $W_{SA}$. Studies show that small reservoirs with $W_{SA}$ of 0.08 ha are capable of exerting an improvement in terms of water supply throughout the entire dry season, even including losses due to $Q_{EV}$ and $Q_I$ (Pinhati et al. 2020).

The results obtained indicated an average $Q_{EV}$ equivalent to 0.000526 $m^3\ s^{-1}$, with maximum and minimum values equal to 0.00189 $m^3\ s^{-1}$ and 0.00011 $m^3\ s^{-1}$, respectively. Nicola (2006) and Fowe et al. (2015) obtained values ranging from 0.00201 $m^3\ s^{-1}$ to 0.0046 $m^3\ s^{-1}$, respectively, in evaluating evaporation rates in reservoirs in the Volta basin regions of Burkina Faso in West Africa. In evaluating a small reservoir in the arid region of northern India, Machiwal et al. (2016) state that the evaporation can reach values of the order of 0.01127 $m^3\ s^{-1}$. Mean evaporation values in some regions of the world ranged from 0.00396 $m^3\ s^{-1}$, 0.00712 $m^3\ s^{-1}$ and 0.00021 $m^3\ s^{-1}$ (Fowe et al. 2015; Althoff et al. 2020).

In this work, the $Q_I$ was approximately 2.06% higher than the $Q_{EV}$, ranging from 0.00038 $m^3\ s^{-1}$ to 0.0101 $m^3\ s^{-1}$, with an average equal to 0.00275 $m^3\ s^{-1}$. Due to the effect of $Q_I$, the results indicated a reduction in volume stored in the reservoir equivalent to 7.6 $m^3\ day^{-1}$. Regardless of the function and purpose of building a small reservoir, it is very important to estimate the infiltration rate, as it directly determines the reservoir's efficiency in storing water (Rodrigues et al. 2007). The infiltration rate can fluctuate over time, decreasing over the life time of small and large reservoirs (Habets et al. 2018; Dashora et al. 2019; Wang et al. 2019).

$Q_I$ is an important variable which must be taken into account in a small reservoir project. For example, considering a constant $Q_I$ equal to 0.0101 $m^3\ s^{-1}$ in the evaluated reservoir, the reservoir would be completely empty in 23 days. Disregarding the effect of $Q_I$ and considering an average $Q_{EV}$ equal to 0.00052 $m^3\ s^{-1}$, the SD model indicates that the reservoir would be completely empty after 989 days. Machiwal et al. (2016) observed that an average $Q_I$ rate equal to 0.0038 $m^3\ s^{-1}$ could decrease the volume stored in a small reservoir in the arid region of northern India in approximately 85 days, concluding that (32%) of stored volume was lost by $Q_I$.

It was observed that the spillway operated 33.7% of the time during the evaluated. More than 60% of the volume of water drained by the spillway was observed in the period from september 4, 2010 to march 20, 2011; this increase in the $Q_{SV}$ value can be explained by the rains that occurred in the period. Studies carried out in several small reservoirs with an average water surface equal to 200 ha indicated that the average amount of water, represent on average 16% of the total outflow in small dams, the results will provide a useful reference for small reservoir design and water resources management worldwide (Fowe et al. 2015; Marín-Comitre et al. 2020).

### 3.4 Assessment of the Risk of Not Meeting the Expected Water Demand

A simulation of the water dynamics in the small reservoir was performed after inserting the $Q_A$ series, which was extended, and the $D_H$ of the agricultural community composed of small irrigators as the input and demand flows in the SD model.

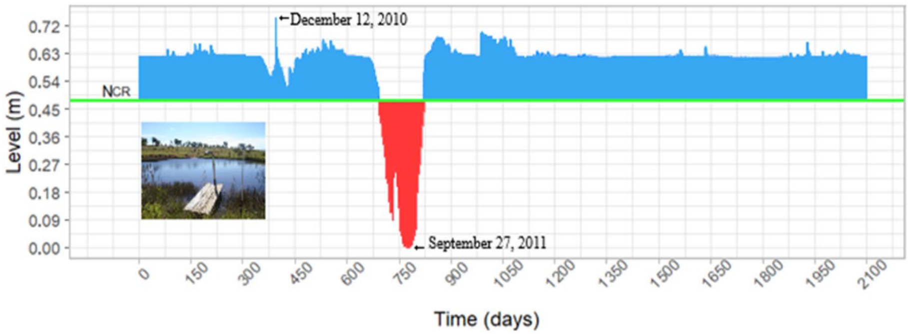


**Fig. 7** Water level variation based on the height of the channel that that allocates water from the reservoir to the human population

The $D_H$ ranged from 0.00133 $m^3\ s^{-1}$ to 0.0881 $m^3\ s^{-1}$, with an average of 0.0212 $m^3\ s^{-1}$. And the variation of $Q_{ABS}$ showed similar behavior to that of $W_{SA}$ in the reservoir. And the lowest losses by $Q_I$ and $Q_{EV}$ were observed with the lowest $Q_{ABS}$ on the days in which the lowest $W_{SA}$ were recorded, ranging from 0.0056 $m^3\ s^{-1}$ to 0.0912 $m^3\ s^{-1}$, with an average of 0.0165 $m^3\ s^{-1}$.

The result show the variation of Hi in relation to the height of the irrigation channel that carries water from the reservoir to the community of small irrigators ($N_{CR}$) (Fig. 7). Whenever the water level is below the $N_{CR}$, it indicates that the farming community is not receiving water to promote irrigation of their crops (area in red below the horizontal line highlighted in green).

The water level in the channel ranged from 0.005 m to 0.73 m, with an average of 0.12 m, reaching a maximum level on December 12, 2010 and a minimum level on September 27, 2011. Based on this result, it is concluded that the water was above the $N_{CR}$ 86.2% of the time; 4.3% of this percentage was spilled by the spillway, meaning 81.9% of the $D_H$ is composed of small irrigators.

The $D_H$ and $Q_{ABS}$ permanence curves intersect at a frequency 82% of the time at a flow rate equivalent to 0.0161 $m^3\ s^{-1}$ (Fig. 8 and Table 4). This means that 18% of the time there will not be enough water in the channel to meet the $D_H$. This suggests that the

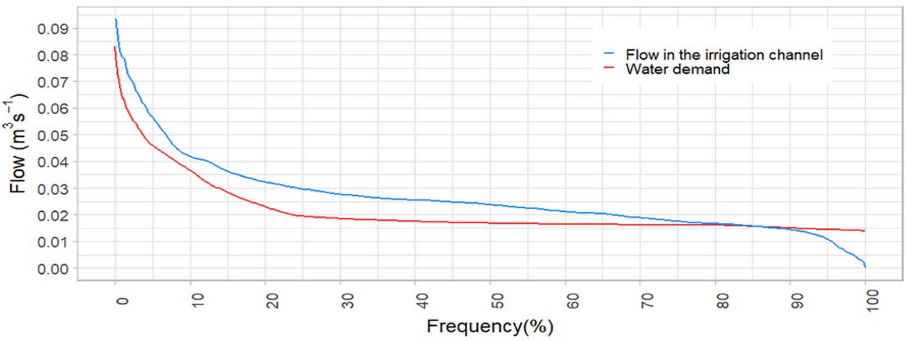


**Fig. 8** Demand ($D_H$) and water supply ($Q_{ABS}$) permanence curves in the isolated reservoir in the Buriti Vermelho River drainage basin, DF, Brazil

**Table 4** Result of water availability and demand for the reservoir evaluated in the Buriti Vermelho River drainage basin, DF, Brazil. (Fr = frequency of being equaled or exceeded; $D_H$ = Water demand; $Q_{ABS}$ = irrigation channel flow)

| Fr (%) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 95 |
|---|---|---|---|---|---|---|---|---|---|
| $D_H$ ($m^3\ s^{-1}$) | 0.036 | 0.025 | 0.019 | 0.018 | 0.017 | 0.016 | 0.016 | 0.0162 | 0.014 |
| $Q_{ABS}$ ($m^3\ s^{-1}$) | 0.041 | 0.032 | 0.027 | 0.025 | 0.023 | 0.021 | 0.018 | 0.0164 | 0.001 |

maximum value of water that can be offered to the community, without risk, is equivalent to a permanence of 82%.

According to the results of the SD model, the water level was above the pipe that connects the reservoir to the irrigation channel 86.2% of the time. The results showed that a reservoir with a storage capacity of 1.889,3 $m^3$ and a maximum $W_{SA}$ equal to 0.0963 ha would be needed to meet $D_H$ up to 95% of the time, as well as a reduction in $Q_{EV}$ and $Q_I$ losses by at least 48%, thus ensuring a more secure flow over time in the irrigation channel. In several countries water managers maintain a safe volume in small reservoirs during the dry season even with $Q_{EV}$ and $Q_I$ control, which reduces the risks of not having water for irrigation and other uses (Martinez Alvarez et al. 2008; Huang et al. 2021; Massuel et al. 2014; Ebrahimian et al. 2020; Zhang et al. 2022).

From this perspective, this information should be taken into account in implementing new small reservoirs which will be built in the future in the Brazilian Cerrado region, mainly to meet the demands for irrigation and other uses of water. Work carried out by Pinhati et al. (2020) indicated that the impact of a single reservoir on water availability is proportional to its size, but also related to its location in the basin. The larger the upstream drainage area, the greater its storage capacity. According to the authors, individual reservoirs with upstream drainage areas < 3 $km^2$ had little impact on local water availability. For example, reservoirs with $W_{SA}$ < 0.08 ha do not contribute to increasing local water availability throughout the dry season.

Evidently, it is not possible to totally eliminate outflows by $Q_{EV}$ and $Q_I$, which would guarantee a safer volume of water in small reservoirs, so the only viability is to reduce these outflows as much as possible. There are several technical strategies which can currently be used to reduce $Q_{EV}$ and $Q_I$ losses. In the case of $Q_I$, implanting layers of compacted clay or geomembrane can contribute to substantially reducing $Q_I$. There are methods based on chemical treatments in the case of $Q_{EV}$ which aim to form a monolayer film, totally or partially covering the surface of the reservoirs (Habets et al. 2018; Machiwal et al. 2016).

In addition, a thin layer of plastic can be used on the water surface. These two methods have the disadvantage of harming aquatic biota. Less invasive alternatives, such as installing solar panels inside the dam, in addition to contributing to reduce $Q_{EV}$, are interesting in the sense of contributing to energy security (Temiz and Javani 2020). Other strategies involve the use of windbreaks at the reservoir edges (Assouline et al. 2008; Reca et al. 2015).

The results indicated that the reservoir has a risk of not supplying the community's water demand for at least 18% of the time due to $Q_{EV}$ and $Q_I$ losses and the undersized reservoir. Thus, a more effective water management plan for irrigation, the main user of the water resource, is essential to achieve water security. Moreover, managing water for agricultural intensification, improving its use and adequate planning for building new reservoirs is vital for water resource management in the Brazilian Cerrado region, especially considering that $Q_{EV}$ and $Q_I$ losses and directly related to the $W_{SA}$ directly imply in the capacity of a reservoir to store and release water. It is not the purpose of this study to provide a detailed analysis of the impacts of small reservoirs on hydrology or future predictions; instead, we try to develop a dynamic simulation model to generate information about the water dynamics in small reservoir, and its capacity to guarantee the water demand along time. Thus, the results demonstrate that a reduction in losses by evaporation and infiltration, to maintain water levels more safely in small reservoirs and ensure supply and demand.

## 4 Conclusions

The results based on the sensitivity analysis indicate that the stored volume presented low sensitivity to the height of the water level, evaporation and discharge of Spillway. Evaporation and infiltration together represented a water withdraw equivalent to 14% of the total inflow. Approximately 81.9% of the total volume of stored water was available to attend water demand despite a risk of not supplying the demand in at least 18% of time. The related research findings of this study could be favorable for guiding the reservoirs construction (optimal size) and management to irrigation and human demand evaluating different variables, and fluxes of the dynamic system model (e.g., infiltration, evaporation), which can provide decision-making premises for water resource utilization in the Cerrado agricultural landscape. We highlight that small reservoir management needs to evaluate different parameters to calibrate efficient and sustainable management of water resources for current and future population demand, and avoid losses due to evaporation and infiltration.

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**Authors Contributions** All authors contributed to the study conception and design. **Alisson Lopes Rodrigues:** Conceptualization, Methodology, Software, Writing—original draft and all authors commented on previous versions of the manuscript. **Lineu Neiva Rodrigues:** Conceptualization, Methodology, Writing—review & editing. **Guilherme Fernandes Marques:** Writing—review & editing. **Pedro Manuel Villa:** Methodology, Software; Writing—review & editing. All authors read and approved the final manuscript.

**Availability of Dataand Materials** I, Alisson Lopes Rodrigues, first author of the manuscript entitled **'Simulation model to assess the water dynamics in small reservoirs'** declare, for the due purposes of data access, availability, right, and use during the development of this research, through the link https://drive.google.com/drive/folders/1mzJeYvY4IQXN_LJPeoviuOavObroeLJ2?usp=share_link. Viçosa (MG), 07/02/2023.

## Declarations

**Ethical Approval** I, Alisson Lopes Rodrigues, the first author of the manuscript entitled 'Simulation model to assess the water dynamics in small reservoirs', declare that the submitted manuscript is original and has not been submitted to more than one publication for simultaneous appreciation. The results were presented clearly, honestly and without falsification or inappropriate manipulation of data. And we certify that we use free software for the development of this work. Viçosa (MG), 07/02/2023.

**Competing Interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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