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Clash of Drought Narratives: A Study on the Role of Small Reservoirs in the Emergence of Drought Impacts

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Key Points:

- We explore the pro's and con's of small reservoirs as drought coping strategy
- Evaporation puts more pressure on surface water storage in semi-arid regions than the demands of small farmers
- Small reservoirs boost the local agricultural production up to five times while reducing the need for emergency water supply

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

In regions characterized by a high concentration of small reservoirs, there is often public debate about the effectiveness of these structures in locally adapting to and mitigating drought impacts, bearing in mind their potential to modify or induce drought events in downstream areas. In this study, we investigated the influence of a Dense Network of Small Reservoirs (DNR) on the emergence and intensification of drought impacts at catchment scale, as well as their local social benefits. This analysis was based on the Socio-Hydrological-Agricultural-Reservoir (SHARE) model, specially developed for this purpose, with a medium-sized catchment in the semi-arid region of Brazil as a case study. We identified that, while a DNR can prolong the effects of a hydrological drought on storage in a large strategic reservoir at the catchment outlet by obstructing surface-runoff connectivity, it plays a crucial role in mitigating drought impacts at a local level. Specifically, the presence of small reservoirs has the potential to boost local agricultural production by up to 5 times compared to scenarios without these structures. In addition, our simulation results suggest there is a notable reduction in the need for emergency water distribution by water trucks in the presence of a DNR. This study highlights the need for a balanced approach to implementing public policies, weighing the local benefits of small reservoirs against the possible downstream impacts on large reservoirs.

Plain Language Summary

This study analyzed the impact of a dense network of small reservoirs in a semi-arid region of Brazil on drought effects. Although there is criticism about the use of these structures because they can influence drought events in neighboring areas, our results showed that, locally, these reservoirs are essential for mitigating the impacts of drought. They may prolong the drought in large reservoirs, but they play a crucial role in reducing local impacts, increasing agricultural production by up to five times. In addition, the presence of these reservoirs considerably reduces the need for emergency water distribution by water trucks. The study highlights the importance of a balanced approach when implementing public policies, considering the local benefits of small reservoirs in relation to the possible impacts on more distant areas.

1. Introduction

There is broad consensus that hydro-climatic disasters should not be analyzed solely from a natural sciences perspective, since the human component plays a relevant role in this context (AghaKouchak et al., 2021; Ribeiro Neto et al., 2022; Sivapalan et al., 2011; Walker et al., 2022). This idea contests any narrative that places a hydrometeorological catastrophe as purely a "natural disaster," since anthropogenic actions are now seen as an endogenous component of the hydrological cycle (Di Baldassarre et al., 2019). In the context of recognizing the importance of the human component in the study of disasters, the field of socio-hydrology emerged, dedicated to evaluating the interactions and relationships between social and hydrological systems, considering how human activities impact water resources and vice versa (Pande & Sivapalan, 2017). Specifically in the context of drought, socio-hydrology sheds light on debates related to the effectiveness of mitigation measures, considering that such actions can induce and/or modify drought events (Van Loon et al., 2016, 2022).

In regions with low water availability, the construction of small reservoirs is a common strategy for adapting to droughts (Cavalcante et al., 2022; Medeiros & Sivapalan, 2020; Walker et al., 2022). However, if executed without adequate planning, these can alleviate impacts in one part of the catchment and intensify them in other parts (Wanders & Wada, 2015), which can generate internal social tensions (Studart et al., 2021) and discussion related to the effectiveness of these structures (Donchyts et al., 2022). This tension was clearly observed by the authors during fieldwork in the semi-arid region of Brazil. It was evident that there were conflicting narratives about the role of small reservoirs versus large reservoirs. Some actors, mostly linked to the government water sector, described small reservoirs as detrimental to the recharge of large (so-called "strategic") reservoirs. In contrast, farmers and some governmental stakeholders mostly from the agriculture sector considered the same small reservoirs as crucial to their water security, asserting that they do not impact hydrological processes of the catchment. One of their arguments was that water in the large reservoirs would evaporate if not utilized, making it more advantageous to use it in the small reservoirs.

Studies show that the collective effect of small reservoirs can reduce the streamflow into the "strategic" reservoirs (Krol et al., 2011; Rabelo et al., 2022; Ribeiro Neto et al., 2022). However, the overall impact and local benefits remain unclear. In this study, we focus on the clash of these two contrasting narratives, exploring the role of Dense Network of Small Reservoirs (DNR) and farmers' water use in the emergence and intensification of drought impacts. We based our study on simulations using a novel socio-hydrological modeling framework capable of simulating hydrological processes, agricultural production, and water resource management at catchment and farm scales, with a medium-sized catchment in the semi-arid region of Brazil as a case study.

2. Methods

We aimed to understand the role of a DNR on the emergence of drought impacts. To this end, we evaluated drought narratives commonly related to reservoir structures, which can be summarized as an evaluation of two conflicting hypotheses:

Downstream impacts hypothesis—The DNR has the potential to induce, aggravate or extend hydrological drought events especially in the downstream reservoirs of the catchment.

Local benefits hypothesis—The DNR does not cause (serious) negative hydrological impacts in the downstream region of the catchment and is significantly beneficial to local farmers.

To evaluate the foundation of these two hypotheses, we divided the analysis into three stages: (a) Analysis of the spatio-temporal distribution of water storage; (b) Analysis of evaporative losses and DNR storage efficiency; (c) Analysis of the local benefits of a DNR. We evaluated both hypotheses using the Piquet Carneiro catchment as case study, which is a socio-environmentally representative area for semi-arid Brazil. Through data analysis and interviews in the field, we identified the main local socio-hydrological dynamics. Based on these dynamics and hydro-meteorological data, we developed a spatially explicit socio-hydrological model and simulated several scenarios to investigate the two hypotheses.

2.1. Case Study

Figure 1 presents the location and some features of the study area. The Piquet Carneiro catchment (170 km^2, Figure 1a) is part of the Brazilian state of Ceará, which is within the semi-arid region of Brazil. The study area presents an irregular annual distribution of precipitation (670 mm/year on average, Figure 1b), but with well-defined wet (4 months) and dry (8 months) seasons. Potential evapotranspiration is high, around 2,000 mm/year. Its shallow soils and crystalline bedrock limit the existence of regional aquifers and perennial rivers, making artificial reservoirs damming intermittent rivers the main source of water during dry periods.

There is a large public reservoir (13.6 Mm^3), centrally managed and therefore called "strategic." From a water management standpoint, its strategic function consists in serving as primary sources for urban water supply and for water trucks when necessary. This reservoir was built with public funding. It is monitored by the Company of Water Management of the State (COGERH) and Ceará Research Institute of Meteorology and Water Resources (FUNCEME). The Dense Network of Small Reservoirs (DNR) of the study area consists of 364 small reservoirs. These are privately owned, built by individuals or communities (sometimes with credit lines provided by governmental programs) to fulfill their own needs. These mainly meet the needs of dairy herds, the main local economic activity, and domestic use. Besides, the vicinity of the reservoirs facilitates agriculture due to higher soil moisture levels (Figure 1h). For all small reservoirs there is only information available on their location and maximum surface area, which was made available by the Ceará Research Institute of Meteorology and Water Resources (FUNCEME, 2021), but their storage is not monitored.

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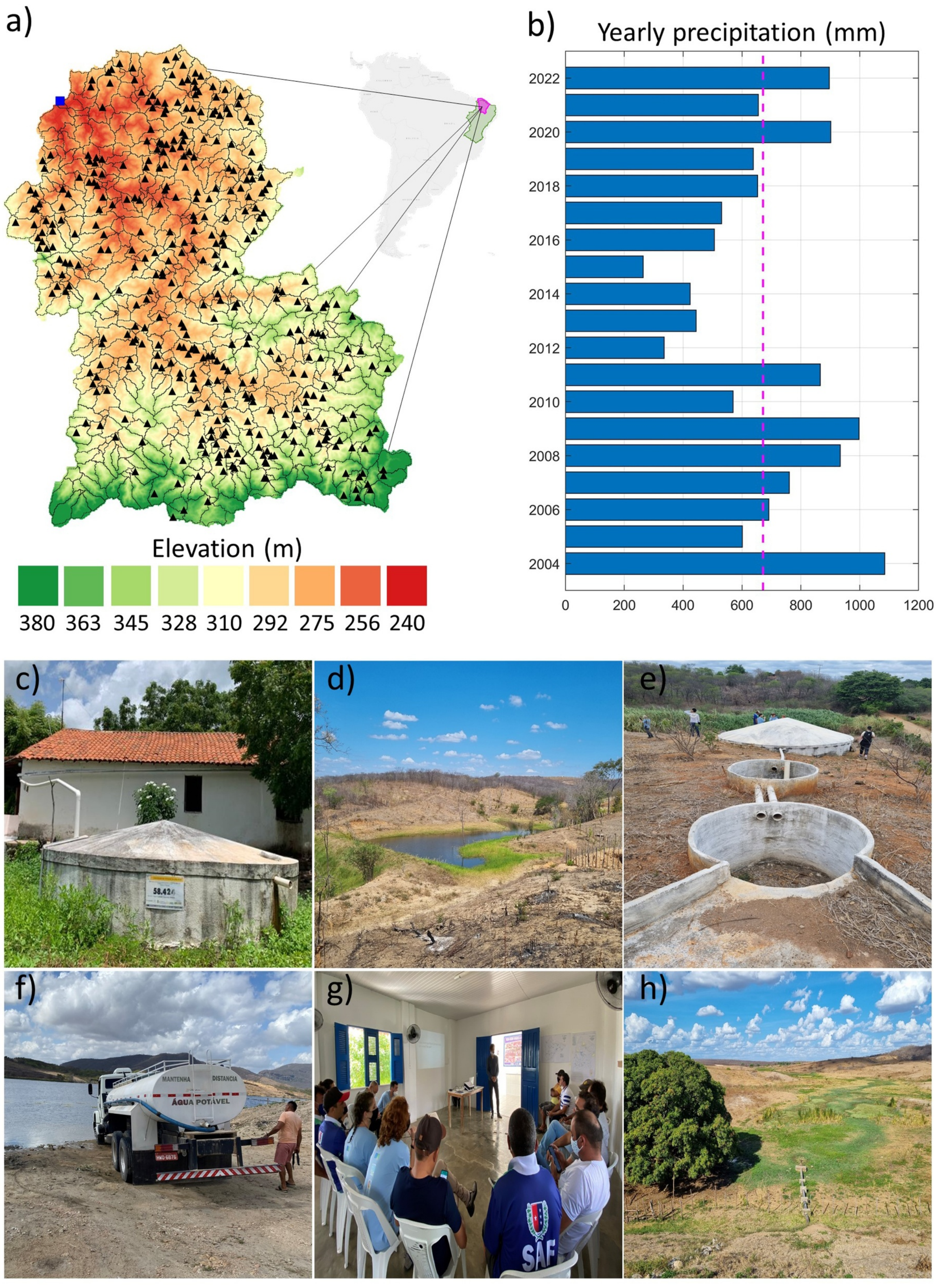

Figure 1.

The last drought event that occurred in the study area was, according to various studies, one of the most intense in the area's recent history. Although the exact duration is not easy to determine, there is common understanding in literature that it persisted for at least six years, from 2012 to 2018 (Costa et al., 2021; Cunha et al., 2018, 2019; Dos Santos et al., 2019). It is estimated that by 2016 the economic losses associated with this drought event were in the order of 30 billion dollars for the entire semi-arid region of Brazil (Marengo et al., 2017). In this same year, 39 out of the 153 strategic reservoirs of Ceará state were completely empty, while another 42 reached levels below the active volume, requiring specific pumping systems to access the remaining water. As a result, 52% of the municipalities, including Piquet Carneiro, faced water-supply interruptions during this drought (E. S. P. R. Martins et al., 2018). This event will be referred to in this study as the 2012–2018 drought.

The majority of the rural population has no access to piped water, therefore the main water source for basic household needs (drinking, cooking and basic personal hygiene) is the rooftop rainwater cistern, which collects water through the house's rooftop (16 m^3, Figure 1c). The second type of cistern is for production purposes, which collects water through surface runoff (52m^3, Figure 1e). However, this type of cistern is more expensive for the population and therefore not as common in the study area as the rooftop rainwater cistern. In this study, our focus was on cisterns used for domestic purposes, hereafter referred to as "cistern." In times of shortage, such as during a drought, water trucks run by the municipality and the army provide emergency water supply to the rooftop rainwater cistern (Figure 1f).

2.2. Socio-Hydrological Modeling Framework

We developed the Socio-Hydrological-Agricultural-Reservoir (SHARE) model, first presented in this study, to investigate the influence of socio-hydrological dynamics on drought impacts at multiple scales. The SHARE model is capable of spatially-explicit simulation of the main hydrological processes, water use, and agricultural production, using a daily time step. This model innovatively combines the water-balance approach following the MGB model (Collischonn et al., 2007), the crop-water productivity of the AquaCrop model (Raes et al., 2009), and a water use model based on information obtained by field observations and interviews. In the SHARE model we also considered the observed drought mitigation measures at different scales, such as cisterns, water trucks and small reservoirs. SHARE's water use model is able to simulate water use from individual households as well as water availability from the strategic reservoir. A summary of the structure of this model is shown in Figure 2. The precipitation and temperature data used in all stages of SHARE come respectively from the rain gauges of Brazil's National Water Agency (ANA) and the meteorological stations of Brazil's National Meteorological Institute (INMET).

The study area was segmented into 512 sub-catchments of 0.33 km^2 on average, connected through drainage channels that were defined using the digital elevation model of the NASADEM product with a horizontal resolution of 30 m (Crippen et al., 2016). This division was made using the IPH-Hydro geoprocessing tool (Siqueira et al., 2016) and was done in such a way as to ensure homogeneity in the areas of the sub-catchment. Each sub-catchment is divided into up to maximum four Hydrological Response Units (HRU, top left of Figure 2): Natural vegetation, agriculture, pasture and non-vegetated areas. The HRUs are the common vertical hydrological processes zones for which the water balance is calculated. First, the runoff per HRU is calculated.

We consider there are three possible types of runoff acting in the sub-catchments, which are surface (Dsup), sub-surface (Dint) and underground (Dbas) flow, as shown in the Water-balance section of Figure 2. The types of runoff vary according to the speed at which they appear and propagate. "Surface runoff" reaches the drainage network quickly, while "sub-surface runoff" has an intermediate speed, and underground runoff is the slowest (Collischonn et al., 2007). Each type of runoff is collected by a different ("hypothetical") simple linear reservoir ("LR" Figure 2). Subsequently, this is added per sub-catchment together with the incoming runoff from upstream sub-catchments. This total runoff is termed Qscatch.

Figure 1. Location and features of the study area. (a) Location and elevation of the study catchment and sub-catchments (see Section 2.2). The blue square and black triangle represent the strategic reservoir São José II and small reservoirs from the DNR, respectively; (b) Yearly precipitation time series. The dashed purple line represents the average precipitation through the study period (2004–2022); (c) Common rooftop rainwater cistern for domestic uses used by farmers in the study area; (d) Example of a small reservoir; (e) Cistern for production purposes that collects water from surface runoff (ground cistern); (f) Water truck being refilled at the only strategic reservoir in the study area; (g) Workshop conducted by the authors of this study with farmers and water practitioners in the study area in November 2021; (h) Crop being sustained by high soil-moisture content due to the presence of a small reservoir.

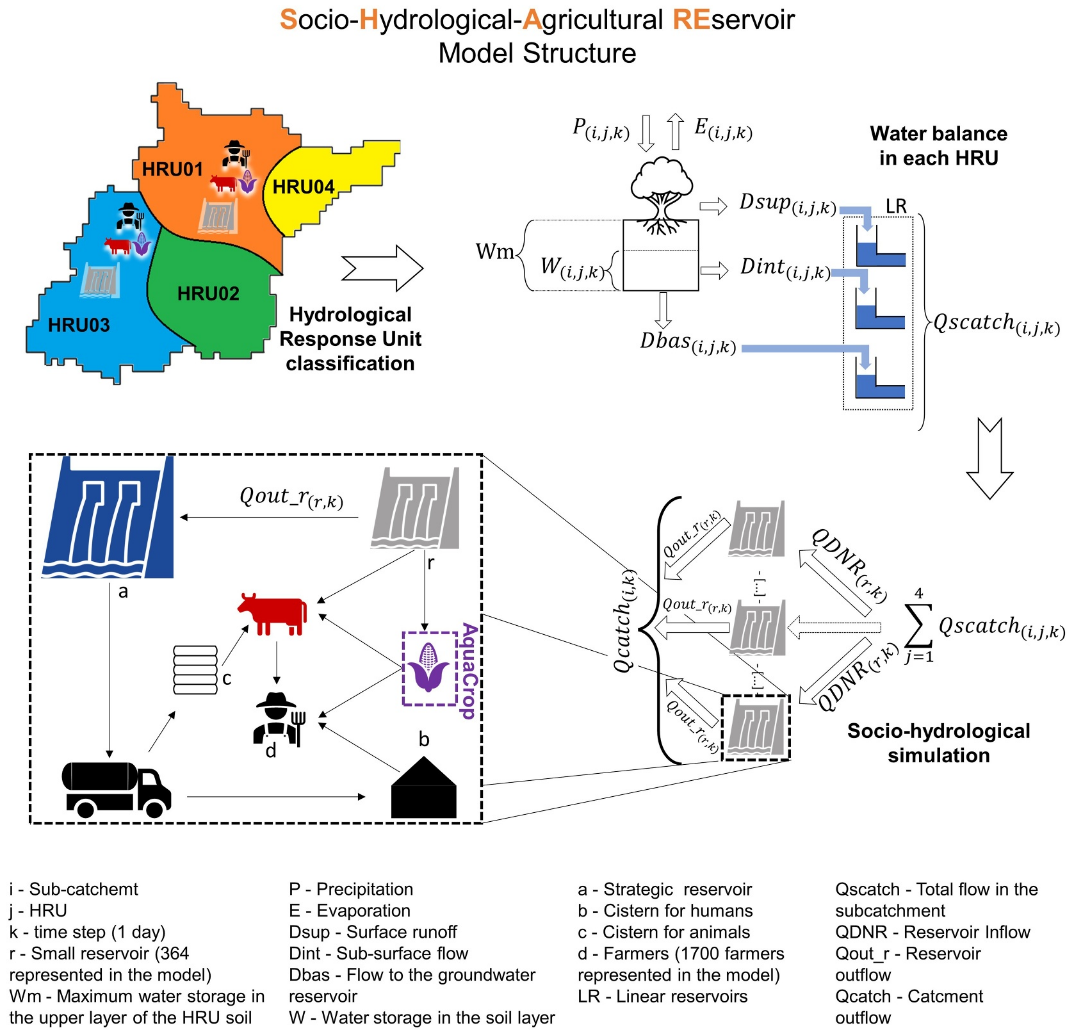

Figure 2. SHARE model structure.

Qscatch is divided over the small reservoirs in the sub-catchment—if there are any. If there are multiple reservoirs in one sub-catchment, the runoff is distributed proportionally to the capacity of the reservoirs (similar to Güntner et al., 2004). For example, a reservoir responsible for 20% of the sub-catchment's total storage capacity will receive 20% of the Qscatch. If there are no small reservoirs or if the storage capacity is exceeded, the runoff is routed to the sub-catchment downstream, reaching it in the next time step. The reservoirs only release water to the sub-catchment immediately downstream when they reach their maximum storage capacity. 211 of the 512 sub-catchments, which accounts for 60% of the drainage area of the study area, have at least 1 small reservoir. More details of the spatial distribution and structuring of the cascade of reservoirs in the study area are presented in Figure S1 in Supporting Information S1. The detailed equations used to calculate the hydrological processes are based on the method presented by Collischonn et al. (2007) and shown in Supporting Information S1.

2.3. AquaCrop

The AquaCrop model (Raes et al., 2009) was developed by the Food and Agriculture Organization of the United Nations (FAO) to simulate the growing process and yield of crops under water stress. It can simulate how water excess or deficit affect crop development. This model can also be used to indicate the optimal water need for irrigation. In this study, AquaCrop was used to simulate the crop yield in all scenarios considered (see Section 2.5). For those scenarios that include irrigation, we consider that the farmers would irrigate following the indication simulated by the AquaCrop. Water for irrigation is supplied from the reservoirs. When these structures are completely dry, the crops are simulated as a rainfed system, which is more vulnerable to agricultural losses due to the precipitation variability of the studied area. This model demands specific parameters related to crop and soil characteristics (e.g., duration of flowering, maximum temperature in which the pollination happens, number of plants per hectare, soil texture) which were derived from M. A. Martins et al. (2018, 2019).

Agricultural production benefits from the increase in soil moisture promoted locally by the presence of small reservoirs. This increase in soil moisture was represented by the reservoir's percolation losses (volume that infiltrate into the ground around the reservoir). Molle (1994) showed that the percolation losses of small reservoirs (maximum storage capacity of less than 2 Mm³) is equivalent to 34% of the evaporated volume. This relationship between percolation and evaporation has also been used by previous works such as Mamede et al. (2018) and Güntner et al. (2004). We consider that this volume "lost" through percolation becomes the "extra" soil moisture that these structures promote and which benefits agricultural production, in which was simulated using the AquaCrop model.

2.4. Socio-Hydrological Modeling Decisions

Daily water usage and agricultural production are simulated by SHARE at daily time step after the completion of the routines for generating and propagating surface runoff. A rural house location product developed by the FUNCEME was used to include farmers in a spatially-explicit way. The following modeling decisions applied to the SHARE model were based on workshops (Figure 1g) and interviews with farmers and water practitioners in the study area. This revealed contextualized details, which led us to simplify the representation of some socio-hydrological dynamics in the model.

Each house represents a family of five, with a daily water consumption (cis_dm) of 14 L per person, supplied primarily by cisterns, which is aligned with the technical recommendation for designing such structures (Silva et al., 1984). The volume stored in each cistern was updated each time step, considering the consumption and the recharge due to rainfall on the sub-catchment to which the house belongs. An interception area of 100 m^2 per home was assumed (roof_area), given the similarity of houses in the region. If a cistern drops to 2% of its capacity (cis_tr), it is supplied with 8 m³ of water from a water truck, which comes from the strategic reservoir in the region (Figure 1f represents exactly this moment). According to interviews, we consider that the most relevant agricultural production to be simulated is maize, which is mainly destined for family consumption and to produce silage for the dairy herd. The annual agricultural production of maize in the study area was obtained from the Brazilian Institute of Geography and Statistics (IBGE). The number of animals was fixed through the simulation period and defined by the ratio between the expected agricultural production (assumed 8ton/ha/year, exp_yield) and an average consumption of silage per cow of 30 kg/day (sil_dm). Secondary water use corresponds (dnr_dm) to 80 l/day per person for domestic activities (e.g., flushing toilets, washing clothes, home cleaning and bathing). Based on the reports collected in the field, we consider that each animal (dairy cow) requires 100 l/day. Farmers primarily use small reservoirs to meet these two demands. When the reservoirs are empty (or don't exist, see item 2.5), secondary water consumption is met by cisterns, and livestock demand is met by water trucks. The water from the water trucks for the livestock is stored in tanks with a capacity of 8 m³ (item c in Figure 2). Table 1 presents a summary of all parameters of the SHARE model also showing the source.

Although water use can vary in response to water availability, as in the case of adopting different agricultural strategies, this possibility was not considered in our simulation. We could not infer this information from the collected data, and there is a lack of validation data (such as storage in small reservoirs) to justify a further increase in model complexity.

Parameters such as daily water demand from cisterns (cis_dm), daily human water demand from the DNR (dnr_dm) and daily animal water demand (herd_dm) have a direct impact on the volume of water stored and the potential need for water trucks. The daily animal silage demand (sil_dm) and expected agricultural production (exp_yield) define the number of animals per farmer, affecting animal water demand. The maximum daily irrigation (max_irr) influences agricultural production and is related to the Aquacrop model in scenarios that include irrigation (see Section 2.5). All the parameters linked to human and animal demands have the potential to affect agricultural production, since these demands compete with irrigation demands. We tested the influence of the fieldwork-derived parameters on the evaluated output metrics (total water storage, agricultural production and number of water trucks) varying the parameters one-at-a-time, considering a scenario that includes irrigation (SC2, see Section 2.5). The results are depicted in Figure S2 in Supporting Information S1. As expected, total

Table 1
SHARE Parameter List

Parameter number	Parameter name	Definition	Source
Hydrological component			
1	Wm [mm]	Maximum water storage in HRU upper soil layer	Calibration
2	Wz [mm]	Lower limit below there is no subsurface flow	Calibration
3	Wc [mm]	Lower limit below there is no ground flow	Calibration
4	Kint [mm/day]	Subsurface drainage parameter	Calibration
5	Kbas [mm/day]	Percolation rate to groundwater parameter	Calibration
6	b [-]	HRU related parameter	Calibration
7	γ [-]	Soil porosity index	Calibration
8	TKS [s]	Surface reservoir time response	Calibration
9	TKI [s]	Sub-surface reservoir time response	Calibration
10	TKB [s]	Ground reservoir time response	Calibration
Water use component			
11	cis_dm [l/day]	Daily water demand from cistern	Fieldwork
12	dnr_dm [l/day]	Daily human water demand from DNR	Fieldwork
13	animal_dm [l/day]	Daily animal water demand from DNR	Fieldwork
14	roof_area [m^2]	Interception area of each house	Data analysis
15	cis_tr [m^3]	Minimum volume that the cistern can reach before an emergency supply by water truck is necessary	Fieldwork
Agricultural component			
16	sil_dm [kg/day]	Daily animal silage demand	Fieldwork
17	exp_yield [ton/ha]	Expected crop yield used to define the fix number of animals	Fieldwork
	–	AquaCrop parameters for maize crop (Table S1 in Supporting Information S1)	E. S. P. R. Martins et al. (2018) and M. A. Martins et al. (2018)

water storage and the number of water trucks respond linearly to daily water demand. All the parameters linked to human and animal demands also affected agricultural production, since these demands compete with irrigation demands. The fieldwork-derived parameters could be tailored to other regions with comparable water systems. In our analysis, the parameters are kept constant among the different scenarios (Section 2.5), which allows for consistent mutual comparison.

2.5. Scenarios Analysis

To evaluate the two diverging hypotheses on the role of the DNR in drought impact emergence, we explored and compared four different scenarios. The first scenario (SC1) represents the current situation in the study area, where small reservoirs are used to meet the water demand of households, livestock and as a way of increasing soil moisture to increase agricultural productivity. The second scenario (SC2) follows SC1 but assumes that all farmers are also able to use the water stored in the DNR for irrigation. The SC2 aims to assess the local benefits and hydrological impacts of intensive use of the water stored in the DNR in the catchment. The third scenario (SC3) follows the same pattern as the SC2 but assumes that the reservoirs of the DNR have 30% increase in storage capacity. This scenario was developed to encompass the narrative that an increase in reservoirs would be beneficial for the local population, which was reported during some field interviews. In the last scenario (SC4) we evaluated the effect of the total absence of the DNR in the study area. The SHARE model was validated using the

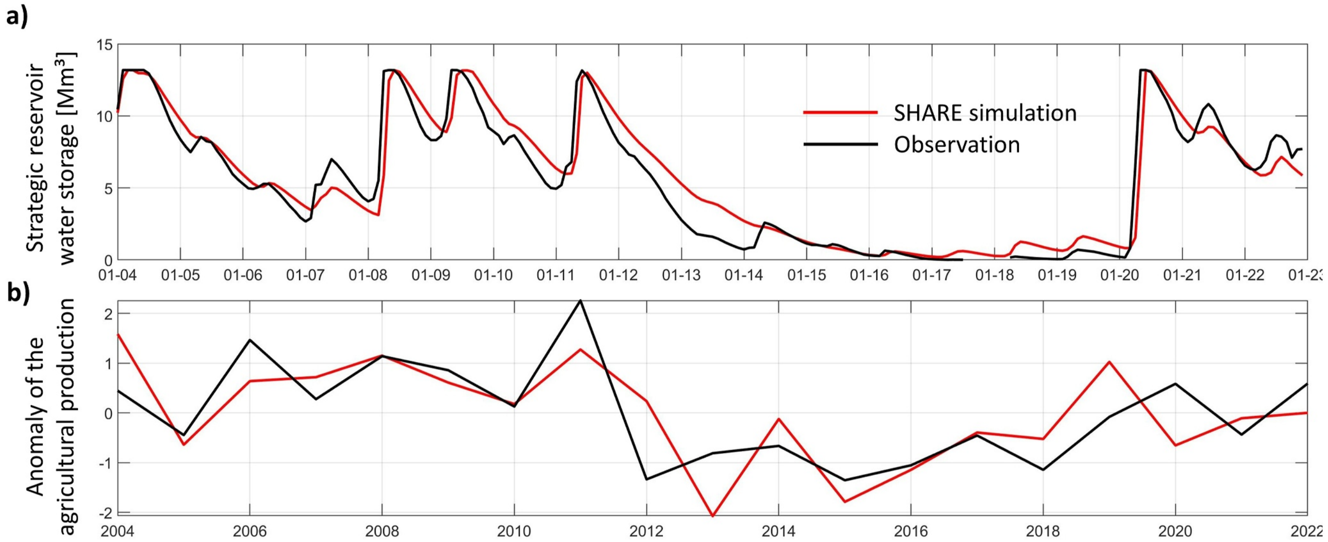

Figure 3. SHARE model validation. (a) Strategic reservoir water storage; (b) Anomaly of agricultural production.

results obtained in SC1 for the volume stored in the strategic reservoir and for simulated total agricultural production. The calibration period was from 2002 to 2010 and the validation period from 2011 to 2022.

The number of farmers (1,700), their location, the total crop area (16 km^2), and the total number of livestock animals (2,383) are exactly the same in all scenarios and do not vary over time. In addition, each farmer had the same crop area and number of animals in all scenarios. We consider the irrigated area to be the same as the crop area. If a reservoir doesn't have enough water to optimally irrigate (based on AquaCrop), the crops would receive less water than ideal for the entire crop area of a given farmer, instead of a reduction in the irrigated/planted area. In the methodological framework applied in our study, we consider that human and animal demand is always met. In other words, there will always be a water truck available to guarantee emergency supplies to meet these demands.

2.6. Evaluation of the Spatio-Temporal Variation of the Water Storage

One way of assessing the downstream impacts of the DNR is by analyzing the spatio-temporal variation in water storage. We propose an innovative approach for this assessment: the Center of Water Storage (CWS), as shown in the following equation. CWS refers to a (hypothetical) location where all the surface water in a catchment could be concentrated, considering the volumes of all the surface storage sources (reservoirs) within the analyzed catchment and their distance to the outlet.

$$\text{CWS} = \frac{\sum_{r=1}^{n} \left(Vr_{(r,k)} \times d_{(r)} \right)}{\sum_{r=1}^{n} Vr_{(r,k)}}$$

where Vr is the volume stored in the reservoir (r) at time step (k) and d is the distance from the considered reservoir to the outlet. This approach is analogous to the physical concept of center of mass and similar to the Downstreamness concept presented by Van Oel et al. (2018), which considers the drainage area of each reservoir instead of the distance to the outlet. Both CWS and Downstreamness assess the temporal variation of water storage throughout a catchment, and can indicate whether there is a greater concentration of water downstream or upstream. The CWS has the advantage of being easier to determine considering a DNR, since the small size of these structures can make it difficult to determine their exact drainage area.

3. Results

3.1. Model Evaluation

Before evaluating the scenarios, the model results for the current scenario (SC1) were compared to available observations. Figure 3 shows the validation stage of the SHARE model based on the SC1 outputs. The data available for validation were the time series of the monthly volume stored in the strategic reservoir and the region's annual agricultural production (maize). It can be seen that the model was able to accurately simulate the volume of the strategic reservoir, with a Nash-Sutcliffe index of 0.89. The model tends to overestimate the observed values, especially in drier periods. This may be due to possible changes in the operating rules, as we did not have access to details of these dynamics; we assumed that during the rainy season, a fixed volume is released that equals the value that is exceeded 95% of the time (based on the observed time series of the volume stored in the strategic reservoir, see Supporting Information). The agricultural production simulated by the SHARE model showed a good similarity to the observed series, with a correlation of 0.68, indicating that the model was able to capture the general trend in the temporal variation of this variable. The results were expressed as an anomaly due to the uncertainties related to the annual planted area, since farmers do not always use all the area available for planting. Although a thorough evaluation of the model is impossible due to a lack of relevant observations, such as water storage in the small reservoirs, these results provide confidence that the model is able to capture the main dynamics relatively well.

3.2. The Spatio-Temporal Distribution of Stored Water

Figure 4 shows the spatio-temporal distribution of surface water storage in the study area, simulated using the SHARE model. The absence of the DNR would significantly increase the volume stored in the strategic reservoir, by up to 11 times during the 2012–2018 drought, compared to a situation where these structures are present. Hence, even though the total storage capacity of the study area is lower without DNR, the total surface water storage (strategic reservoir plus DNR) in the drier periods is higher (e.g., 2012–2018 drought Figure 4c), by up to five times. This can be attributed to an increase in the system's storage efficiency, by concentrating all the surface water in a single, larger reservoir instead of distributing part of the system's water in smaller structures that promote proportionally greater evaporative losses. The evaporative losses and storage efficiency aspects of the DNR are also part of the narrative related to the "*Downstream impacts hypothesis*" and will be discussed in more detail in Section 3.3.

During the 2012–2018 drought in SC4 (the scenario without DNR) the strategic reservoir would have reached alarming levels (<50%) 2 months later than actually recorded. Considering critical level (<25%) this difference would have been 15 months. The length of periods in these ranges varied considerably between SC4 and the other scenarios. Without the small reservoirs, the strategic reservoir would have remained below 50% of total storage capacity for 82 months (36% of the studied period) and below 25% for 30 months (13% of the studied period). For the other scenarios, it would have been approximately 132 months (58% of the studied period) below 50% and 80 months (35% of the studied period) below 25% of total storage capacity.

Figure 4d presents the spatio-temporal distribution of water as a function of distance from the catchment outlet (vertical axis) and considering the stored volume in relation to the storage capacity for SC1, which represents the current situation of the study area. The average volume in relation to the maximum storage capacity of the reservoirs (percentage of surface storage) at a given distance from the outlet was evaluated for each time step of the studied period. For example, the reservoirs that are around 12 km from the outlet had a storage volume close to 70% of their storage capacity during the rainy season of 2021, while those around 6 km away were at about 18% of their capacity at that time. During the analyzed period, there were two drought episodes in the study area: a weak/milder one from 2006 to 2008 and the last, more severe one from 2012 to 2018, as mentioned above. During these droughts, the reservoirs emptied evenly regardless of their position in the catchment but the recovery of stored water occurred from upstream to downstream.

From 2004 to 2012, the Center of Water Storage (CWS) did not show major seasonal variations throughout the year. With the onset of the drought in 2012, the CWS remained close to the strategic reservoir due to a uniform reduction in the volume stored in the studied area. However, from 2014 onwards, the CWS moved upstream, indicating that even when the strategic reservoir was on the verge of depletion, there was still water stored more upstream in the study area, in the DNR. Between 2016 and 2020, the small reservoirs delayed the recovery of

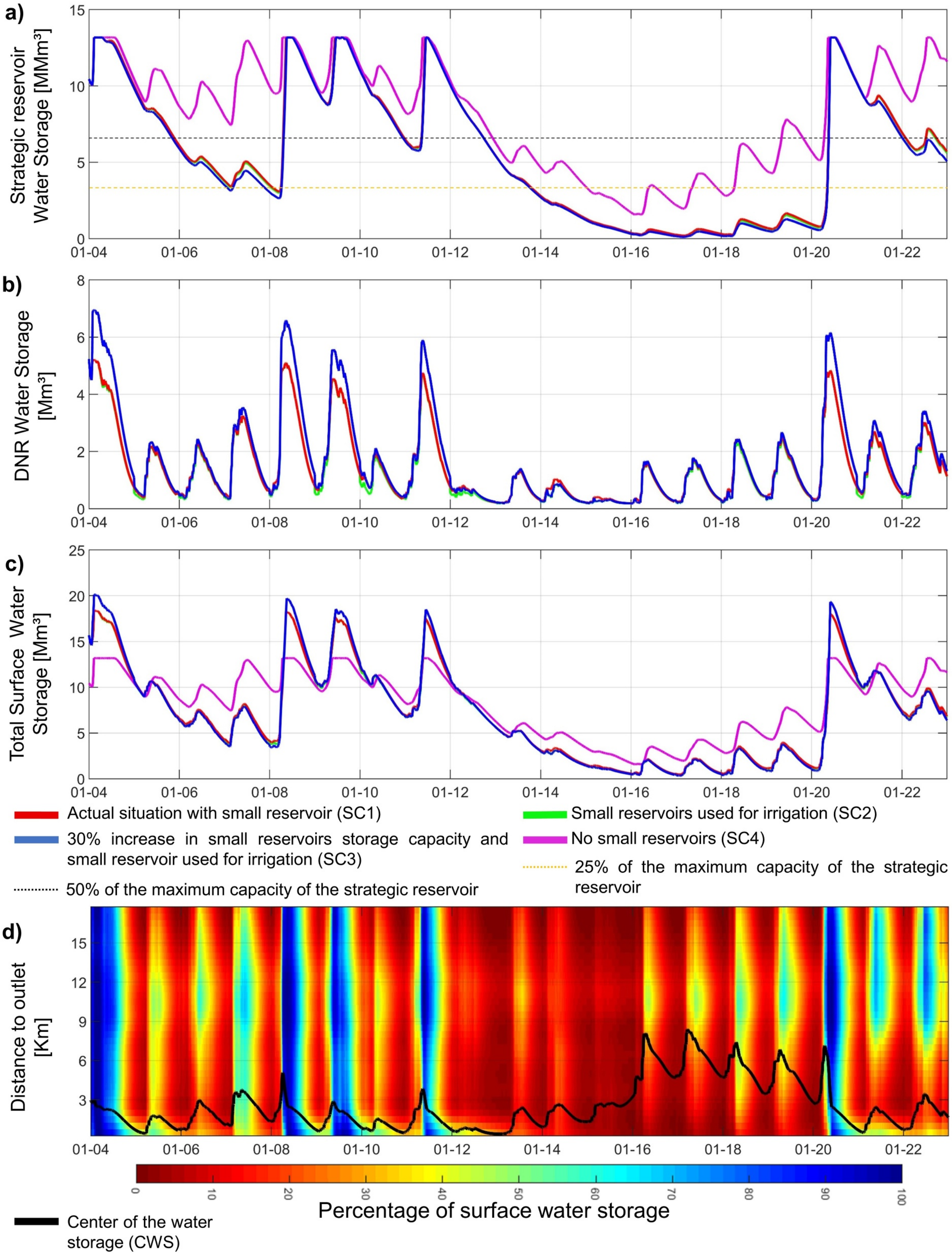

Figure 4. Spatio-temporal water storage distribution. Panels "a," "b," and "c" present the volume variations in the strategic reservoir, Dense Network of (small) Reservoirs (DNR), and total surface water storage (TSWS), respectively. Panel "d" illustrates storage distribution based on distance from the catchment outlet, related only to the current scenario (SC01). The black line in this figure indicates the distance of the Center of Water Storage (CWS) to the outlet.

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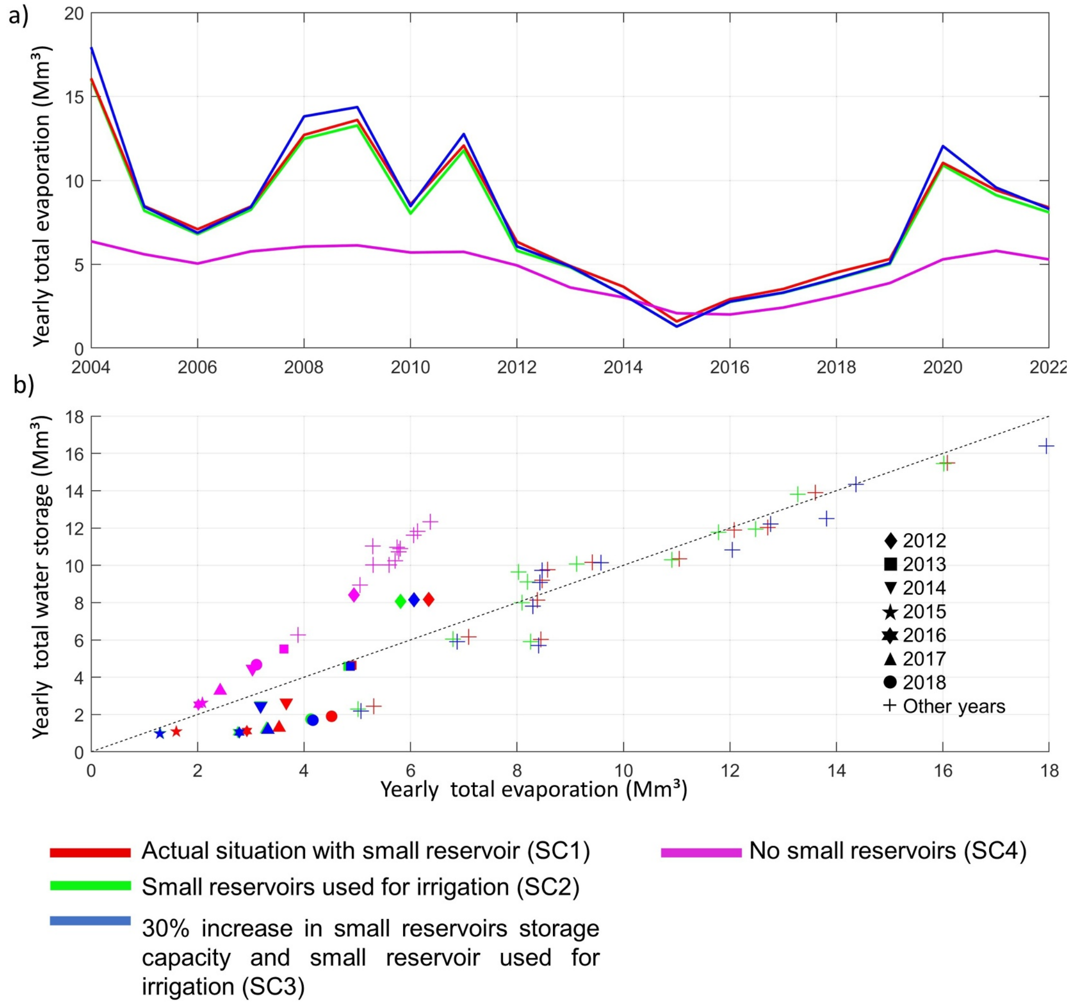

Figure 5. Water storage efficiency. (a) Yearly total evaporation; (b) Ratio between total water storage and total evaporation in the catchment.

storage in the strategic reservoir, evidenced by the gradual recovery of the volume stored in the area, which occurred from upstream to downstream. The existence of the DNR influences the recharge of the strategic reservoir, delaying its recovery and prolonging the impacts of drought events. On the other hand, the lack of major difference between the storage in the DNR and in the strategic reservoir, when comparing the scenarios with and without irrigation (Figures 4a and 4b) indicate that the way farmers use water from small reservoirs does not influence dominant hydrological processes related to the recharging of these structures. This also indicates that the emptying of small reservoirs is dominated more by evaporation losses than by local anthropogenic demands.

3.3. Water Storage Efficiency

An argument often used against small reservoirs is that these structures are inefficient from a storage point of view due to relatively high evaporation losses. Evaporation from reservoirs is evaluated in Figure 5a, which shows the annual evaporation for both small and strategic reservoirs. Only between 2014 and 2016 was there similarity between the evaporative losses of all the scenarios and this coincides with the most intense period of the 2012–2018 drought. In the other periods, the small reservoirs caused, on average, 60% more evaporation, while increasing surface water storage capacity by only 17% in comparison to the scenario without the DNR (SC4).

On average, evaporation accounts for 35% of the total storage capacity in the scenario without the small reservoirs (SC4) and 42% in the scenario with the small reservoirs (SC1). The storage efficiency of each scenario was also analyzed using the ratio between annual stored volume and evaporation, shown in Figure 5b. In this scatter plot, the pair of values below the 1:1 line indicate that the total water storage at the end of the year is lower than the total evaporated over the same period. We consider this situation to be an inefficient water storage system and the optimal alternative would be indicated by a pair of values as high as possible above the 1:1 line. On average, 1.37 Mm³ evaporated for every 1 Mm³ stored. The lowest performance in this ratio was 2.7 Mm³ (2016) evaporated for every 1 Mm³ stored. Thus, in addition to delaying the recovery of the strategic reservoir, the DNR also considerably reduces the system's water storage efficiency, especially during drought events.

3.4. Analyzing the Benefits of a DNR

Despite delaying the recovery of the strategic reservoir, and higher evaporation rates, small reservoirs are still defended as coping strategies by farmers (*Local benefits hypothesis*). Therefore, we also explored the benefits that small reservoirs can bring. Figure 6 shows annual agricultural production (maize) and the use of water trucks for all four scenarios considered. Interestingly, small reservoirs boost agricultural production, which is on average 5 times higher in the scenario without irrigation (current situation, SC1) and approximately 8.7 times higher in the scenarios with irrigation (SC2) when compared to the scenario that does not consider the existence of the reservoirs (SC4). Furthermore, without the small reservoirs there would be greater dependence on water trucks for livestock farming, up to 15 times higher, as we assumed that farmers would not abandon this activity due to local water shortage. Thus, the small reservoirs substantially increase agricultural production and decrease dependency on water trucks.

Further increasing the storage in small reservoirs, as foregrounded by some farmers in the field, does not equivalently increase production. SC3, which assumes that the small reservoirs are 30% larger, shows an average agricultural production 1% higher than SC2, suggesting that the amount of water stored in the reservoirs already meets most of the demand for irrigation. Irrigation can increase production by 66% on average and 130% during droughts. However, this extra demand for water would accelerate the depletion of the reservoirs, increasing the need for water trucks during times of water shortage. In short, the use of water from small reservoirs has a greater influence locally, by alleviating drought impacts through boosting agriculture and reducing the need for water trucks, than on downstream water availability, when considering the water storage in the strategic reservoir.

4. Discussion

The Downstream impacts hypothesis considers that a Dense Network of (small) Reservoirs (DNR) can induce or modify hydrological droughts, especially in the downstream part of the catchment. During normal and above-average rainy seasons, most of the reservoirs are recharged, maintaining the storage balance, with small reservoirs not obstructing runoff connectivity or water availability in downstream areas. In other words, in years of normal precipitation, the DNR does not have significant hydrological impact on downstream areas, in line with the *local benefits hypothesis*. However, an intense precipitation deficit results in an imbalance in the recharging-emptying dynamic, leading to a storage deficit that spreads spatially and temporally throughout the catchment. The inefficiency of reservoir storage in small reservoirs, reflected in the relationship between evaporated and stored volumes (Figure 5), is central to understanding the narrative that relates the presence of a DNR to the occurrence of hydrological droughts (water shortages in downstream areas). The lower the relative water volume stored in the DNR, the higher the relative evaporative loss. This implies that the same volume of recharge will have different effects on total water availability depending on how full the small reservoirs are. This pattern is directly related to maintaining the storage deficit in the downstream reservoir, since when the small reservoirs are completely full they contribute to maintaining the connectivity of surface runoff, which is crucial for the overall recharge of water storage in the area.

The influence of the DNR on the spatial-temporal recharge of the catchment storage could easily be observed through the Center of Water Storage (CWS), a novel method presented in this study. This indicator is a weighted average of the volumes stored in relation to the distance from the outlet (strategic reservoir in this case), indicating where proportionally more water is stored. Analyzing CWS allows us to observe that during an intense drought there can be a gradual shift in the CWS, moving from downstream to upstream (Figure 4d). An increase in precipitation (indicating the ending of the precipitation deficit period) intensifies this shift, showing a higher concentration of water upstream while areas closer to the outflow maintain low storage volumes. This means that the water-storage recovery after intense precipitation deficit period is delayed due to the presence of a DNR and that recovery only occurs slowly in an upstream-downstream direction.

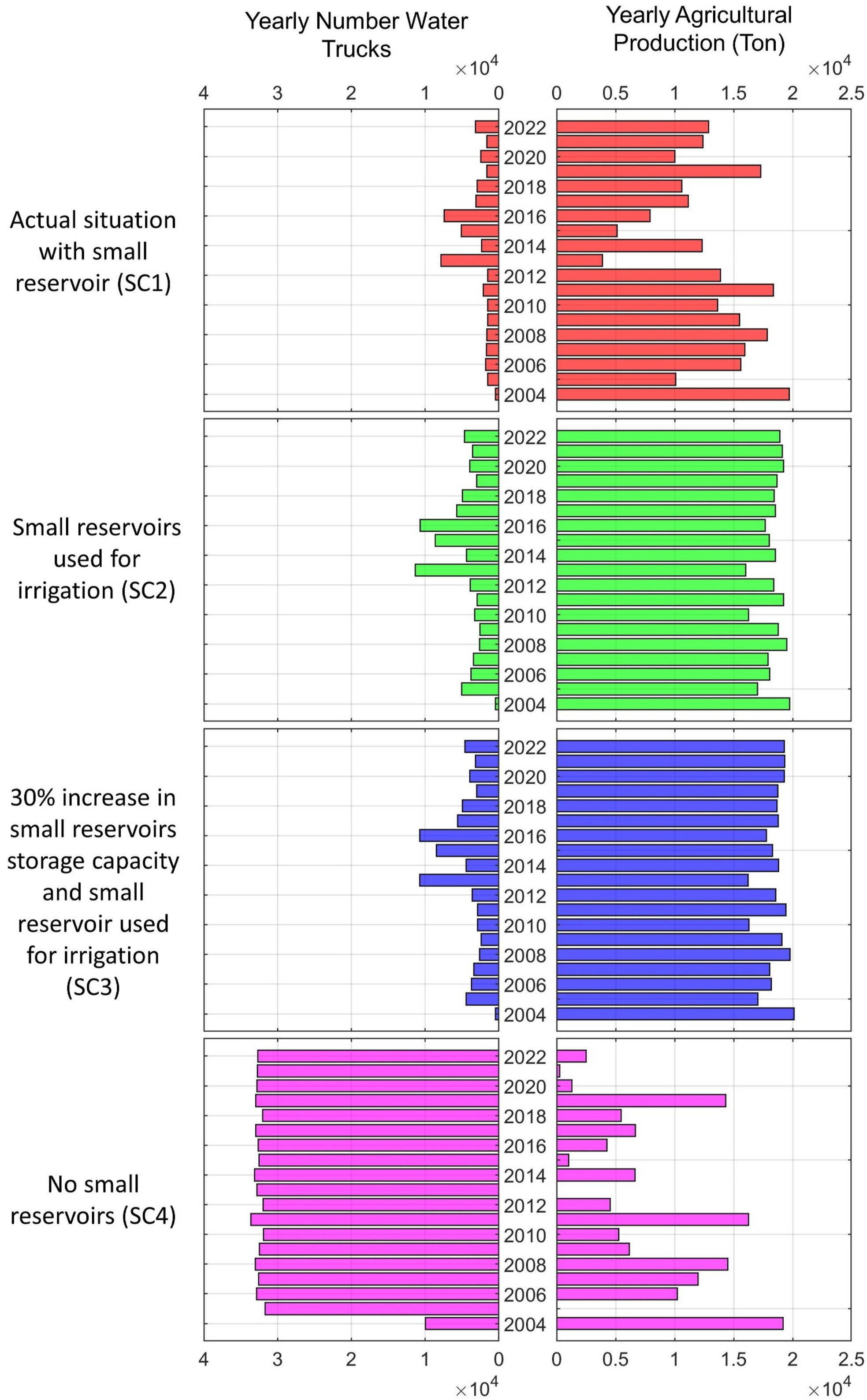

Figure 6. Assessment of the benefits of a Dense Network of (small) Reservoirs (DNR).

The effect of the DNR on the water storage recovery associated with simulations of the volume stored in the strategic reservoir confirms the hypothesis that the DNR has the potential to induce and modify hydrological droughts (*Downstream impacts hypothesis*). The triggering of drought events was evident by observing that the volume in the strategic reservoir would only have reached more alarming storage levels (<25%) approximately 15 months later than recorded (Figure 4a). Our results indicate evidence that the main modification of drought events due to the existence of the DNR is related to the delay in the recovery of volumes in large reservoirs located downstream, such as the strategic reservoir in our study area. Consequently, this prolongs the impacts of hydrological drought for populations dependent on these water resources. To be even more precise in the delay estimation, it would be necessary to enhance the spatial representation of the small reservoirs in the study area and evaluate the sensitivity of the results to surface flow propagation being simulated at smaller time steps. Other studies that have analyzed the effect of DNR on hydrological droughts agree with the findings in this study, including Ribeiro Neto et al. (2022) who followed an approach based on the Drought Cycle Analysis and hydrological-modeling studies by Krol et al. (2011), Malveira et al. (2012), Mamede et al. (2012), Rabelo et al. (2021), Rabelo et al. (2022), and Colombo et al. (2024).

The confirmation of the *Downstream impacts hypothesis* does not necessarily invalidate the *Local benefits hypothesis* of the DNR. Although the presence of small reservoirs can influence the hydrology of the catchment, the way in which farmers use the water storage from small reservoirs does not seem to have a major impact on downstream water availability. This was also observed by Lima et al. (2023) who analyzed the impact of intensive water use from small reservoirs on strategic reservoirs. Even with intense water use for irrigation from small reservoirs, the water storage in strategic reservoirs would remain almost unchanged. Without the existence of the DNR, the demand for water supplied by water trucks would increase greatly (15 times higher on average, assuming no adaptation in water-use activities) and local upstream agricultural production could be reduced by up to 5 times. The *Local benefits hypothesis*, even though it may disregard the hydrological impact of DNR at the catchment scale, suggests clear benefits for local upstream farmers using water from small reservoirs, which we confirmed. However, an increase in the storage capacity of the DNR, advocated for by some farmers, would not substantially influence these benefits. The absence of a DNR would lead to an increased dependence on water trucks and reduced agricultural production, resulting in subsequent socioeconomic impacts on the population. The water supply by water trucks is not only expensive but also inefficient. The decrease in agricultural production would lead to a greater demand for imported forage to meet local livestock demand, which would increase virtual-water transfers into the area. Furthermore, lower agricultural production in this region would result in higher public spending on social programs to transfer income to the affected populations (Cavalcante De Souza Cabral et al., 2023; Cavalcante et al., 2022; Walker, 2024).

The absence of a DNR would reduce the total accumulated volume in the study area, but on the other hand, it would increase the volume overflowed by the strategic reservoir when it reaches maximum capacity (Figure S3 in Supporting Information S1). This could result in benefits for downstream areas. Exploring this effect would make it possible to analyze another type of clash of drought narratives: the management of water resources between upstream and downstream in large river catchments. Some studies, such as Van Langen et al. (2021) and Van Oel et al. (2018), have addressed these interactions between upstream and downstream in catchments characterized by multiple strategic reservoirs, but without considering the effects of DNR. In Colombo et al. (2024) also addressed this issue and considered considering the DNR effect in a simplified way which do not account for the water use related to the small reservoir neither their potential local benefits. Therefore, the methodology presented here can contribute to future work aimed at studying the impact of a DNR in this context in more detail.

In the absence of an accessible rural water supply system for farmers, or other ways of storing water more efficiently, small reservoirs fulfill their role in reducing local drought impacts, even if they prolong/induce/modify drought impacts downstream. Nonetheless, DNR is far from being the best solution for water storage in a semi-arid region, mainly due to the high evaporation losses inherent to such structures. Furthermore, an increase in the evaporation and reduction in precipitation in the semi-arid region of Brazil is projected due to climate change (Cook et al., 2020; Marengo, 2020; Marengo et al., 2019; Papalexiou et al., 2021). The modification of the climate regime of this region can potentially reduce the window of opportunity for the use of water stored in the DNR and intensify the local drought impacts. Future research could evaluate the effects of climate change and land use and land cover evolution in semi-arid regions, based on a socio-hydrological framework such as the SHARE model, also considering water storage and supply alternatives that are less susceptible to high evaporation rates, such as ground cisterns (Figure 1e) and rural water-supply systems.

Socio-hydrological modeling, an interdisciplinary approach that integrates hydro-meteorological and social aspects to analyze human-water systems faces a number of methodological challenges. The main one is the representation of anthropogenic dynamics, both due to the lack of observational data and the high complexity of these dynamics. The lack of socio observational data, for instance, made it unfeasible to include a representation of farmers' behavioral variations in water management and agriculture in the SHARE model. The high complexity of the dynamics related to the availability of water trucks meant that we had to impose certain simplifications in our analysis. Although we considered universal access to this resource in the simulation without any adapting behavior during low water availability, in reality, remote regions and political aspects influence this availability. Including these "nuances" would require new parameters and/or structures in the model, which would not necessarily result in more accurate simulations, since the absence of data related to the total yearly number of water trucks makes it impossible to calibrate or validate this kind of information. As such, the number of water trucks simulated with SHARE is indicative of the amount of water required to sustain the system as is.

The clash of drought narratives, translated in this study into the analysis of two hypotheses regarding the potential of DNR to influence hydrological droughts, hides the pitfall of analyzing complex problems without a proper holistic view. Using a "conventional" hydrological model would probably enable reaching a similar conclusion as we did about the hydrological impacts that DNR causes downstream, which confirm the *Downstream impacts hypothesis*. However, such an approach would not easily allow evaluation of the local benefits that these structures bring and that partially confirm the *Local benefits hypothesis*.

Although the SHARE model presents certain limitations, it accurately simulated the volume in the strategic reservoir and the temporal trends in local agricultural production. Moreover, SHARE can be used to address drought impact forecasting methods, which can contribute to better preparedness and response to drought (AghaKouchak et al., 2023). To improve the representation of the anthropogenic dynamics, more interaction with local communities would be needed, creating opportunities for activities based on citizen science and scientific communication. Incorporating information from such interactions could increase interdisciplinarity in drought assessment studies, since hydrology and meteorology alone do not provide the means towards comprehensively understanding the relevant human dynamics related to drought (Ribeiro Neto et al., 2023).

5. Conclusion

We analyzed the effect of a Dense Network of (small) Reservoirs (DNR) on the emergence of drought impacts at the catchment scale and contrast this with the local benefits of these structures. This analysis was motivated by the ongoing clash of drought narratives often observed in semi-arid regions, related to the ideas of supporting or opposing the presence of these small reservoirs. These narratives are also motivated by the idea that the DNR is one of the causes of inequality in water availability in semi-arid regions. The clash of drought narratives was summarized in this study into the evaluation of two hypotheses: *Downstream impacts hypothesis* which considers that DNR has the potential to induce, aggravate or extend hydrological droughts and the *Local benefits hypothesis* which considers that DNR only promotes local benefits for farmers. We developed the Socio-Hydrological-Agricultural-Reservoir (SHARE) model to explore these conflicting hypotheses and applied it to the situation in drought-prone Piquet Carneiro catchment (170 km^2) in the semi-arid region of Brazil. This catchment contains 364 small reservoirs located upstream of one large strategic reservoir. The DNR can directly influence the recharge of downstream reservoirs, including the strategic one, by obstructing the surface-runoff connectivity, which prolongs the impacts of a hydrological drought. Furthermore, DNRs contribute to higher evaporation rates. These arguments favor the narrative that describes small reservoirs as an inappropriate drought adaptation strategy. In this study, we have shown that this narrative does not tell the whole story. We showed that the water demand that puts the highest pressure on the water availability in the study area is evaporation and, in this sense, rapid use of the water stored in the small reservoirs generates the greatest benefits. In the absence of better alternatives that promote equality in terms of water security, small reservoirs may particularly reduce the impacts of droughts locally. This is mainly due to the increase in agricultural production by up to 5 times compared to the scenario without small reservoirs, as well as a drastic reduction in emergency supply situations relying on water trucks. These contrasting narratives indicate the challenges in understanding human-water dynamics, yet this should not discourage further investigation. With this study, we have taken a step further in reconciling socio-dynamics into models.

The SHARE model proved to be a useful tool for better understanding the complex socio-hydrological processes of a semi-arid region. Limitations of the approach relate to simplified representation of the spatio-temporal variation in agricultural management by farmers. Overcoming these limitations, would require a comprehensive interdisciplinary approach which would allow this model to support local water resources management. Given the growing pressure on water resources, even more so in the face of uncertain climate change scenarios, it is imperative to further develop tools like the SHARE model to support sustainable and equitable water resource management strategies. Doing so may help to avoid drought-management decisions that are only informed by one perspective in a clash of drought narratives.

Data Availability Statement

The code of the SHARE model, the location of the small reservoirs and farmers, and the meteorological stations used in all simulations are available online via: G. Ribeiro Neto, (2023).

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