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Projected Climate Change Impacts on Rainwater Harvesting in Brazilian Single-Family Houses

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Abstract

Climate change is expected to impact rainfall amount, seasonality, and dry/wet patterns, with direct implications for rainwater harvesting systems. This study aims to quantify how future rainfall may affect rainwater harvesting systems across Brazil by combining multi-model climate projections with a daily water balance model. A single-family social housing archetype (60 m^2 roof area; four occupants; 150 L/day/person; non-potable demand equal to 30% of total demand) was simulated for 652 Brazilian cities, using bias-corrected daily rainfall from the CLIMBra dataset and nineteen climate models. Historical conditions were compared with near-future and far-future projections under the SSP2-4.5 and SSP5-8.5 scenarios. Historically, the greater potential for potable water savings has occurred in wetter, less seasonal climates, such as those in the North. In contrast, more seasonal and drought-prone areas, such as the Northeast, showed lower reliability. In future climates, most models indicate relative reductions in the potential for potable water savings in the North, Northeast, and Centre–West, with larger reductions under SSP5-8.5 and in the far-future scenarios. The South shows the most significant divergence between models and may increase the potential for potable water savings in some projections. On the other hand, in the South, the volume of rainwater harvesting system overflow increases under future scenarios. This work contributes to the literature by delivering a national-scale, multi-model, uncertainty-aware evaluation of rainwater harvesting performance under non-stationary rainfall regimes.

Keywords: climate models; rainwater harvesting; resilience; design; built environment

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1. Introduction

Climate change, together with rapid urbanisation, represents one of the most significant challenges for the built environment, increasing the complexity of maintaining adequate standards of quality, health, and safety for urban populations [1–3]. Rising temperatures and altered rainfall regimes directly affect building performance and resource demand [4]. Buildings are both contributors to and victims of climate change, accounting for a substantial share of greenhouse gas emissions while having their design and operation

strongly influenced by climatic variables [5,6]. Consequently, integrating climate information into building and urban infrastructure planning has become important to support robust technical performance under future conditions [7].

In Brazil, the effects of climate change have become increasingly evident across the 12 bioclimatic zones. The country faces a combination of altered rainfall patterns and greater hydrological variability, which challenge the management of water and energy systems, the development of public policies, and the establishment of city master plans [8–12]. These transformations have direct implications for urban infrastructure, public health, and water and energy security [11,13,14]. Given the regional diversity, from humid tropical climates in the North to temperate zones in the South, the impacts are heterogeneous, requiring locally tailored adaptation measures and planning tools [15].

Projected climate scenarios for Brazil suggest substantial alterations in non-stationary rainfall regimes, including shifts in intensity, duration, and seasonality [12,16,17]. For buildings and cities, these changes are critical because they influence stormwater management systems, roof drainage design, and the potential for rainwater harvesting. In some regions, more intense short-duration events may increase the volume conveyed to urban drainage systems, whereas in others, longer dry periods can reduce water availability for rainwater harvesting [17,18]. Understanding these dynamics is fundamental to climate-responsive design; therefore, non-stationary approaches to Intensity–Duration–Frequency (IDF) curves and scenario-based simulations to manage uncertainty are increasingly adopted [19,20].

Adaptation in the built environment encompasses a range of strategies that aim to minimise vulnerability and enhance resilience to climate impacts [3,21]. In this context, decentralised water management strategies, particularly rainwater harvesting, are sensitive to shifts in rainfall seasonality and intermittency, which can affect system yield, storage requirements, and overflow behaviour [22]. Therefore, integrating climate projections into building design standards and planning processes is essential, enabling decision-makers to anticipate risks and design buildings that operate effectively under future conditions [23–26].

Sustainable Urban Drainage Systems (SUDS) have gained prominence as practical tools for addressing both mitigation and adaptation challenges related to rainwater [27,28]. SUDS combine environmental benefits with functional urban performance, thereby reducing the problems associated with conventional systems. Among SUDS measures, rainwater harvesting stands out for its dual role in managing stormwater and supplementing water supply, increasing resilience to climate change impacts on water availability/security. When properly designed, such systems can reduce runoff volumes conveyed to urban drainage systems, alleviate pressure on municipal networks, and enhance building sustainability by providing a non-potable alternative water source [29–32].

The performance of rainwater harvesting systems depends on several drivers, including rainfall patterns, roof characteristics, storage capacity, and user demand profiles [33]. Previous studies have evaluated system efficiency and economic feasibility under historical conditions; however, few have incorporated climate change projections into their assessments [34–37]. Integrating future climate data enables more accurate estimates of system reliability and identifies potential reductions in rainwater or shifts in optimal storage sizes across regions. Future rainfall projections exhibit substantial inter-model uncertainty and reflect non-stationary rainfall regimes. Thus, the incorporation of bias-corrected projections across multiple models is increasingly recommended to support robust and risk-aware rainwater harvesting design [38–40].

The interaction between climate change and rainwater harvesting is complex, as variations in rainfall and evaporation directly affect system yield and reliability. In regions expected to experience drier climates or more irregular rainfall, the contribution of rainwater systems to urban water resilience may decrease if they are not adapted to new conditions.

Conversely, areas projected to receive more intense rainfall may present opportunities for system optimisation, contingent on design adjustments that account for altered rainfall patterns and storage dynamics [41].

However, to the best of our knowledge, no national-scale assessment of residential rainwater harvesting performance across Brazil has been reported to date. In contrast to the predominantly single-location or specific-case-study approaches in the literature, this study provides a nationwide evaluation across 652 Brazilian cities using bias-corrected daily rainfall and 19 future climate models from CMIP6, reported by scenario and time horizon, and explicitly characterising inter-model variability. Moreover, beyond potable water savings, we include an operational indicator based on the frequency of overflow days.

In light of these challenges, this study is guided by the following research question: "To what extent can climate change impact rainwater harvesting systems in residential buildings in Brazil?"

To address this question, the study quantifies the potential impacts of climate change on the performance of residential rainwater harvesting systems by jointly assessing (i) reductions in potable water demand and (ii) changes in frequency of overflow days (i.e., days with discharge to the drainage network). This assessment is based on projections from global climate models, combined with local rainfall data, under different emission scenarios. By doing so, the study provides scientific evidence to support the adoption of design guidelines and public policies that promote sustainable water use in buildings, contributing to the broader debate on climate resilience and more adaptive built environments in Brazil.

2. Materials and Methods

The method developed in this study was designed to assess the impact of climate change on rainwater harvesting systems in Brazil. A comparison is then made between rainwater-harvesting simulations with varying tank sizes. Figure 1 shows the scientific method used in this research. Regarding implementation strategies, we chose the Netuno programme [42] because it is widely validated and used in computational simulations of rainwater harvesting in Brazil [33,43,44]. Python scripts (version 3.13) were also used to evaluate the results and conduct statistical analysis. During the development of the Python scripts, Gemini 3.0 Pro was used in an agentic workflow to support the creation of the visualisations and provide statistical analysis. All scripts were reviewed by the authors to ensure the logic and processes were correct. Also, Grammarly was used to improve the text's readability throughout the manuscript.

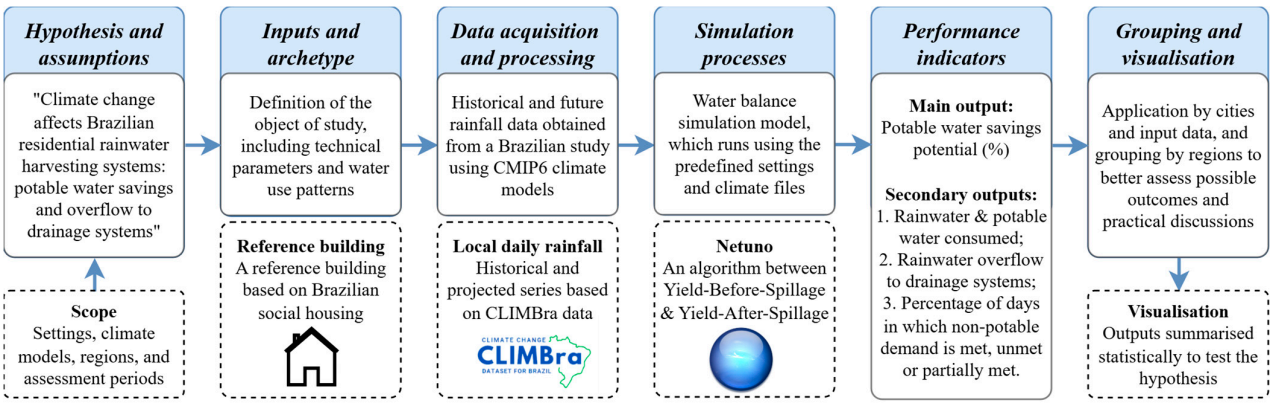

Figure 1. Flowchart of the methodology proposed in this research.

The research methodology, detailed in Figure 1, follows a structured logical flow. The process begins with defining the scope and assumptions. In sequence, inputs and

archetypes are selected, including social housing (60 m^2 of roof and four residents) and four tank-sizing scenarios (S1 to S4), representing market practice. In the data acquisition and processing stage, daily rainfall series from the CLIMBra dataset were used, covering 19 CMIP6 climate models and two emission scenarios (SSP2-4.5 and SSP5-8.5) for 652 Brazilian cities. These data informed the daily water-balance simulation performed by the Netuno programme, which operates with an intermediate logic between the Yield-Before-Spillage (YBS) and Yield-After-Spillage (YAS) formulations, ensuring balanced estimates of rainwater consumption and overflow. Finally, the application and statistical analysis involved processing 61,940 files via Python scripts, enabling the synthesis of performance indicators to test the hypothesis that climatic non-stationarity significantly impacts the potential for rainwater harvesting and tank overflow.

2.1. Object of Study

This study evaluated the rainwater harvesting system of a Brazilian social housing adapted from LabEEE [45], and similar to the archetype of Schaefer et al. [46]. A single-family, one-storey reference dwelling was used to provide a controlled baseline for assessing climate-driven changes in rainwater harvesting performance. The object of study comprises a building with a roof area of 60 m^2 and four residents, yielding 15 m^2 per person. The rainwater harvesting system considered in this study comprises gutters, vertical pipes, first-flush devices, pumping stations, upper and lower rainwater tanks, and other necessary devices. Figure 2 illustrates the object of study and the respective rainwater harvesting system considered in this study.

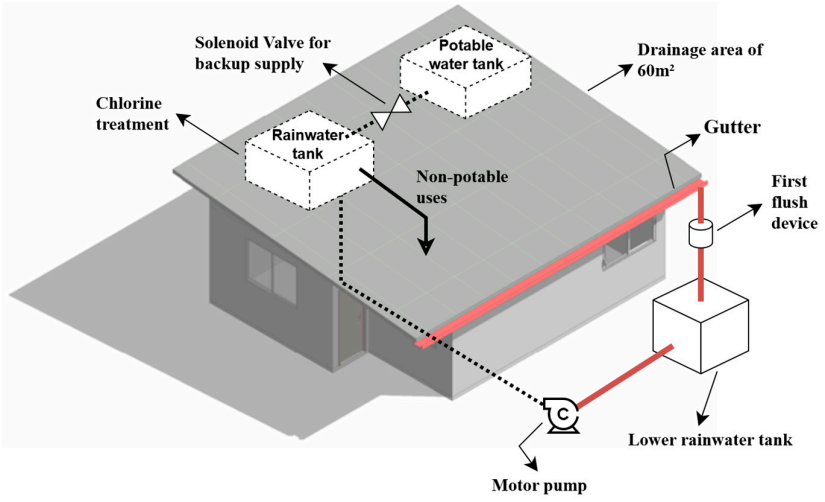

Figure 2. Building information model of the assessed buildings.

2.2. Historical and Future Rainfall Database

Historical and future rainfall data were obtained using the procedures described by Vaz et al. [47]. The procedures draw on data from the CLIMBra database [48] and employ appropriate processes to organise and prepare the data for use in the Netuno programme [42]. It was decided to simulate data for each Brazilian city with more than 50,000 inhabitants, totalling 652 locations (listed in Supplementary Data S1), using 19 climate models from the sixth round of the Coupled Model Intercomparison Project (CMIP6). Such data comprise bias-corrected historical and future scenarios under two different Shared Socioeconomic Pathways (SSP) emissions projections: SSP2-4.5, representing a business-as-usual scenario, and SSP5-8.5, representing a high-energy-intensity scenario in the coming decades [49,50]. Finally, for the future rainfall time series, rainfall was divided into two periods: before and after 1 January 2060, enabling the assessment of near- and far-future results. Table 1 shows

the rainfall data used in this research. The data can also be visualised in the dashboard presented by Vaz et al. [47], which includes leading indicators and trends of current and future rainfall.

Table 1. Characteristics of the rainfall data used in the study.

Parameter	Value
Cities assessed	652 cities with more than 50,000 inhabitants.
Timeframe	From 1 January 1980 to 31 December 2013 in historical data; from 1 January 2015 to 31 December 2059 in near-future scenarios; and from 1 January 2060 to 31 December 2100 in far-future scenarios. These dates are derived from the available data in the CLIMBra database. [1]
Scenarios	Historical data and future data in SSP2-4.5 and SSP5-8.5
CMIP6 models	Nineteen climate models from Japan (MRI-ESM2, MIROC6), Europe (EC-EARTH3, CMCC-ESM2), Russia (INM-CM4-8, INM-CM5), Norway (NorESM2-MM), Germany (MPI-ESM1.2-HR), Australia (ACCESS-ESM1-5, ACCESS-CM2), Taiwan (TaiESM1), China (NESM3), South Korea (KIOST-ESM, KACE), USA (GFDL-CM4, GFDL-ESM4), UK (HadGEM3-GC31-LL, UKESM1.0), and France (IPSL-CM6A).
Total number of files	652 cities and 5 timeframes/scenarios, and 19 models, totalling 61,940 files

Notes: [1] The timeframe has different sizes in years because Ballarin et al.'s classification [48] was used for the historical period (between 1980 and 2013). Subsequently, future CLIMBra data were separated to ensure they span entire decades and have similar historical series sizes.

CLIMBra provides daily rainfall series that are bias-corrected against observations using Quantile Delta Mapping (QDM). Because QDM applies a distributional (quantile-based) adjustment to the original daily sequence without resampling or reordering days. As such, the temporal ordering of wet and dry days is retained, thereby preserving the temporal dependence structure inherent to each climate model while correcting systematic biases in the marginal distribution. Extreme rainfall characteristics are accordingly adjusted during the distributional correction. However, QDM is designed to preserve the model-projected climate-change signal in the corrected series (i.e., changes relative to the historical baseline are maintained) [47,48]. The 19 CMIP6 models were treated as equally weighted, with mean values counted as one vote per model. Unless stated otherwise, averages reported in this study (for rainfall indicators and for rainwater-harvesting performance metrics derived from the Netuno simulations) were calculated as the arithmetic mean across the 19 models for each city, emissions scenario, and time frame. Inter-model variability was retained and reported as the basis for uncertainty assessment.

Rainfall data were also examined to identify the rainfall variables most correlated with the performance of the rainwater harvesting system. The indicators considered in this study were selected based on the existing literature [33,44,51–55], which identifies total annual rainfall and seasonality as key factors influencing rainwater harvesting performance. The seasonality index follows the formulation of Istchuk and Ghisi [56] and was obtained from the Vaz et al. [47] database. Equations (1) and (2) describe the calculation of the respective indices.

$$PRCPTOT_y = \sum_{P_{d,y} \geq 1\text{mm}} P_{d,y}, \quad (1)$$

$$SI_y = \frac{1}{P_{ar,y}} \cdot \sum_{m=1}^{12} \left| P_{m,y} - \frac{P_{ar,y}}{12} \right|, \quad (2)$$

where $P_{d,y}$ is the daily rainfall in the assessed year "y" (mm/day); $P_{ar,y}$ is the total annual rainfall of the assessed year "y" (mm/year); m is each of the months on the assessed year "y" (month); $P_{m,y}$ is the monthly rainfall for the month "m" in the assessed year "y" (mm/month); $PRCPTOT_y$ is the annual rainfall on wet days for the assessed year "y" (in which daily rainfall exceeds 1 mm) (mm/year); SI_y is the seasonality index of the assessed year "y" (non-dimensional); y is the assessed year.

2.3. The Impact of Future Rainfall Data on Rainwater Harvesting Performance

The rainwater harvesting simulation was conducted using a daily water balance that accounted for volumes of rainwater collected, consumed, and overflows. This type of simulation is widely studied in the literature, with different algorithms available for calculation, depending on the order of procedures adopted in the system. This is the case with the Yield-Before-Spillage (YBS) and Yield-After-Spillage (YAS) algorithms, which are commonly used. In this context, the Netuno programme, in version 4, represents an intermediate approach between the two, yielding results that are neither conservative nor optimistic, unlike YAS and YBS [42]. Equations (3)–(8) show the calculation method presented in the Netuno programme, version 4 [42].

$$\text{Rain}_{efec,i} = \max\{\, 0 \;\&\; (Rain_{\,i} - FF)\}, \tag{3}$$

$$V^i_{flows} = Rain_{efec,i} \cdot A \cdot k_{runoff}, \tag{4}$$

$$V^i_{begin} = min\left\{\, (V_{cap}) \;\&\; \left(V^{i-1}_{end} + V^i_{flows}\right) \right\}, \tag{5}$$

$$R^i_{consumption} = min\left\{\, \left(R^i_{demand}\right) \;\&\; \left(V^i_{begin}\right) \right\}, \tag{6}$$

$$V^i_{end} = V^i_{begin} - R^i_{consumption}, \tag{7}$$

$$W_{save} = 100 \cdot \frac{\sum_{i=1}^{n} R^i_c}{\sum_{i=1}^{n} P^i_{demand}}, \tag{8}$$

where V^i_{flows} is the rainwater volume intercepted by the harvesting surface on day i (L/day); $Rain_i$ is the rainfall volume on day i (mm); $Rain_{efec,i}$ is the effective rainfall volume on day i (mm); FF is the first-flush volume which is discarded to improve rainwater harvested quality (mm); A is the harvesting area (m^2); k_{runoff} is the coefficient of available rainwater in the harvesting surface after losses (non-dimensional); V^i_{begin} is the volume of rainwater in the tank at the beginning of the day i (L); V_{cap} is the maximum volume of water in the tank (L); V^{i-1}_{end} is the rainwater volume available at the end of the previous day (L); $R^i_{consumption}$ is the rainwater consumed on day i (L); R^i_{demand} is the rainwater demand in day i (L); V^i_{end} is the volume of rainwater available at the end of the day i (L); W_{save} is the potential for potable water savings obtained through the use of rainwater (%); P^i_{demand} is the total (potable and non-potable) water demand in day i (L); i is the specific day assessed; n is the number of days simulated (days).

Therefore, one must define all the input variables required for the simulation. These data were considered stationary to maintain focus on evaluating climate models. Daily water demand was set at 150 L/day/person, as reported by SNIS [57] and by Vaz et al. [58], based on the mean consumption in Brazil. The non-potable use percentage was set at 30%, a representative value for Brazilian residential non-potable water use, primarily in toilets and outdoor cleaning [59]. The roof runoff coefficient was considered to be 0.80. According to Ribeiro and Marinoski [60], this value corresponds to ceramic roofs, which are the type used in the building.

Finally, the first-flush discharge was set to 2.0 mm, following the Brazilian national standard ABNT NBR 15527 [61], which provides guidelines for rainwater harvesting systems. The quality of the first discharge, however, is not stationary. Maykot et al. [62] show that the preceding dry period significantly affects water quality parameters (including turbidity, apparent colour, total coliforms, and *E. coli*). As climate change is expected to modify rainfall intermittency and preceding dry periods, runoff quality, and, consequently, the effectiveness of a fixed first-flush of 2.0 mm may also change over time. Thus, because water quality is not simulated here, it was conservatively assumed that the collected rainwater would be chlorinated prior to use. The sensitivity of tank sizing to climate change is addressed in Section 2.4.

2.4. The Impact of Tank Sizes on Rainwater Harvesting Performance

Previous studies have evaluated the sensitivity of rainwater harvesting systems to input parameters, including analyses performed using Netuno [42]. These studies indicate that the number of inhabitants is the most influential parameter, followed by rainwater tank size, potable water demand, and, lastly, catchment area. Given the computational cost of the simulations, this study did not explore a wide range of parameter combinations. Instead, a representative single-family household was adopted, with consumption patterns based on values reported in the literature.

Among the design parameters, rainwater tank size is particularly critical because it directly affects system performance and may require adjustment across different rainfall regimes. Accordingly, different design scenarios were considered, each defined by a specific combination of lower and upper tank volumes. Four tank configurations were assessed to represent practical design choices for Brazilian single-family dwellings. The tank capacities selected reflect combinations widely available at local stores and span a realistic range of storage capacities typically used in urban households. The tank sizes selected are as follows:

- Upper tank size of 150 L and lower tank size of 310 L;
- Upper tank size of 250 L and lower tank size of 500 L—Reference value used for the comparison of climatic files;
- Upper tank size of 500 L and lower tank size of 1000 L;
- Upper tank size of 1000 L and lower tank size of 2000 L.

2.5. Summary of Scenarios Assessed

Thus, a total of four input selections was evaluated for each of the 61,940 current- and future-climate files available in Brazil. Table 2 summarises the scenarios evaluated. The objective of this study is to focus the analysis on the variation between climate models and the impact of the designer's response to climate change through the choice of tank size. In other words, the objective is to understand what to expect in the future and the consequences for the design of rainwater harvesting systems. Sensitivity of rainwater harvesting systems' performance to non-climatic inputs (e.g., rainwater demand assumptions, water quality, first-flush, and operating rules) has been extensively investigated in the literature [63–65], consistently demonstrating their influence on potable water savings and system reliability [66–72].

Table 2. Characteristics of the rainwater harvesting simulation used in the study.

Parameter	Considered Values
Rainfall data [2]	Ranged between the 61,940 files in Table 1
Harvesting area (m^2) [1]	60

Table 2. *Cont.*

Number of people (people) [1]	4
Daily water demand (L/day/person) [1]	150
Non-potable demand (% of the total demand) [1]	30
Roof runoff coefficient (n.d.) [1]	0.80
Upper rainwater tank (L) [2]	S1: 150/S2: 250/S3: 500/S4: 1000
Lower rainwater tank (L) [2]	S1: 310/S2: 500/S3: 1000/S4: 2000
First-flush (mm) [1]	2 mm (following standard NBR 15527)

Notes: n.d. = non-dimensional. [1] Fixed inputs adopted in all simulations (not varied). [2] Scenario-dependent inputs varied according to the available values and the tank sizes used.

2.6. Simulation Outputs and Statistical Procedures

Ultimately, statistical procedures were employed to evaluate the impact of changes in variables on the potential for potable water savings. In total, seven outcome variables were considered after running the Netuno programme and used to evaluate the performance of rainwater harvesting systems:

- "potential_savings": variable describing the potable water saving potential, corresponding to the amount of potable water that is no longer consumed after the system is installed. The maximum theoretical value is equal to the non-potable demand (%);
- "average_rainwater_consumption": variable describing the average daily consumption of rainwater, considering how much was actually consumed in the simulation (L/day);
- "average_potable_water_consumption": supplementary variable to the previous one, corresponding to the average consumption of water imported from other sources, such as purchase from the utility company (L/day);
- "average_rainwater_overflow": variable that assesses, after managing the volumes to be stored in the lower and upper tanks, as well as consumed during the day, the volume of rainwater that overflows into the drainage network (L/day);
- "period_when_demand_is_fully_met": percentage of days within the evaluated period in which the rainwater demand is completely met by the system considered (%);
- "period_when_demand_is_partially_met": percentage of days in the evaluated period in which the rainwater demand is partially met by the system under consideration (%). Rainwater is used, but the volume available in the upper tank does not meet all the demands for the day;
- "period_when_demand_is_not_met": percentage of days in the evaluated period in which rainwater demand is completely met by the potable water system, without supplementation from the rainwater harvesting system (%). In other words, no rainwater is available for use.

For specific visualisations, the data were grouped by region or state to better understand larger-scale trends. Brazil has 27 federal units classified into five macro-regions: North, Northeast, Centre–West, Southeast, and South. More details on the classification of regions are available in Supplementary Data S1, with references from the Brazilian Institute of Geography and Statistics (IBGE). The IBGE also provides a map of Brazilian states, regions, and capitals [73]. For these visualisations, the option was to use the average values from the models' results in Netuno. The exception occurs in the inter-model section, where a more detailed description of the differences in results across the available future rainfall models is provided. The analysis compared absolute and relative changes. The absolute change is the simple difference between future and historical values. The relative

change expresses this as a percentage of the historical baseline. This percentage is useful for comparing trends across models without focusing on their specific future values.

Finally, the Supplementary Data present additional statistical details and evaluations of the simulation results and the rainfall data used. This was done to avoid overburdening the paper and to ensure understanding of the statistical data, the sensitivity of the variables, and the relationship between rainfall profiles and system performance. Supplementary Data S2 presents the changes in total annual rainfall in wet days (≥1 mm) (PRCPTOT), showcasing differences among the climate models. Supplementary Data S3 presents future versus historical results for 250/500-L tanks, plotted by model and scenario. Supplementary Data S4 presents the inter-model agreement on changes in potable water savings between the historical and future scenarios. Supplementary Data S5 presents the sensitivity analysis of the simulation results. Finally, Supplementary Data S6 presents a linear regression of rainfall indices versus potable water savings.

3. Results

3.1. Projected Changes in Brazilian Rainfall Patterns Regarding Rainwater Harvesting

The database provided by Vaz et al. [47] and used in this study contains nine consolidated rainfall indicators for each year, including historical and future data. As indicated above, changes in the two indicators most directly related to rainwater harvesting system performance were assessed: total annual rainfall in wet days (≥1 mm) (PRCPTOT) and the Seasonality Index (SI). Figure 3 shows a summary of models using the SI and PRCPTOT indicators, including the average value for the far-future versus historical results. The comparison is based on the multi-model mean values (among cities and models) and thus does not address inter-model comparisons, which are described in Supplementary Data S4.

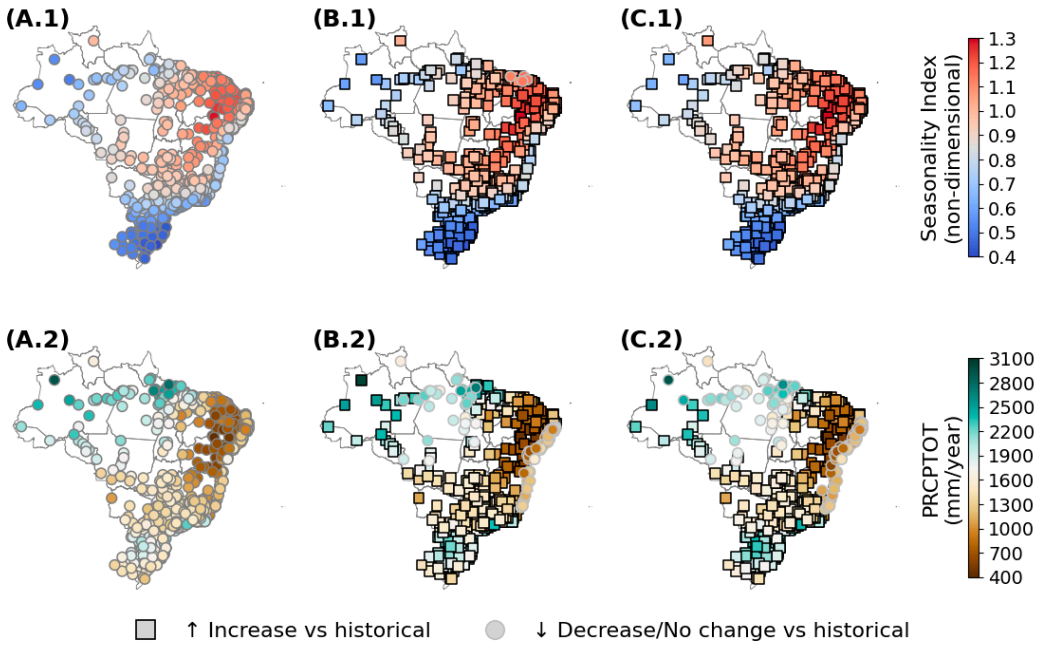

Figure 3. Spatial distribution of multi-model averages for (**A.1**–**C.1**) Seasonality Index (SI) and (**A.2**–**C.2**) Annual Wet-days Rainfall (PRCPTOT) in (**A.1**,**A.2**) historical baseline, (**B.1**,**B.2**) SSP2-4.5 far-future scenario, and (**C.1**,**C.2**) SSP5-8.5 far-future scenario.

Figure 3A.1,A.2 indicates high spatial heterogeneity in Brazil's historical rainfall regime across the IBGE macro-regions. The North combines high PRCPTOT with low to moderate seasonality, consistent with a comparatively well-distributed rainfall pattern throughout the year. In contrast, the Northeast is characterised by low PRCPTOT and high

seasonality, indicating rainfall concentrated in a shorter wet season and longer dry spells. The Centre–West generally shows intermediate PRCPTOT alongside moderate to high seasonality, reflecting a marked alternation between wet and dry seasons. The Southeast shows intermediate to high PRCPTOT but also clear spatial heterogeneity in seasonality, with areas displaying more concentrated rainfall regimes than others. Finally, the South shows lower seasonality (suggesting more evenly distributed rainfall throughout the year), while PRCPTOT remains mostly intermediate, with localised wetter pockets.

However, average values are insufficient to characterise future projections, as there is substantial inter-model variability. For example, Figure 4 shows the distribution of the seasonality index across models. In this case, the underlying data for each distribution (i.e., each violin plot) comprises the values from all 652 cities across all years within a given classification. For enhanced interpretation, three categories are assumed based on the median: increase (I)—an increase of more than 0.03 between the median of the baseline scenario and SSP5-8.5 far-future; decrease (D)—a decrease of more than 0.03; and constant (C)—a variation within these two ranges. It can be observed that 14 models showed an increase, the other 5 models showed variations of less than 0.03, and none had a negative variation. The same is presented for the PRCPTOT in Supplementary Data S2 in the Supplementary Data, using a threshold of 100 mm/year for increases or decreases. Both thresholds were selected to yield a difference of approximately 2% of the maximum amplitude between the lowest and highest values across Brazilian cities, based on historical data. The minimum PRCPTOT and SI are 50 and 0.13, while the maximum values are 5074 and 1.67, respectively. Note that the violin plot shows the data distribution, with the width indicating the frequency and the line indicating the median.

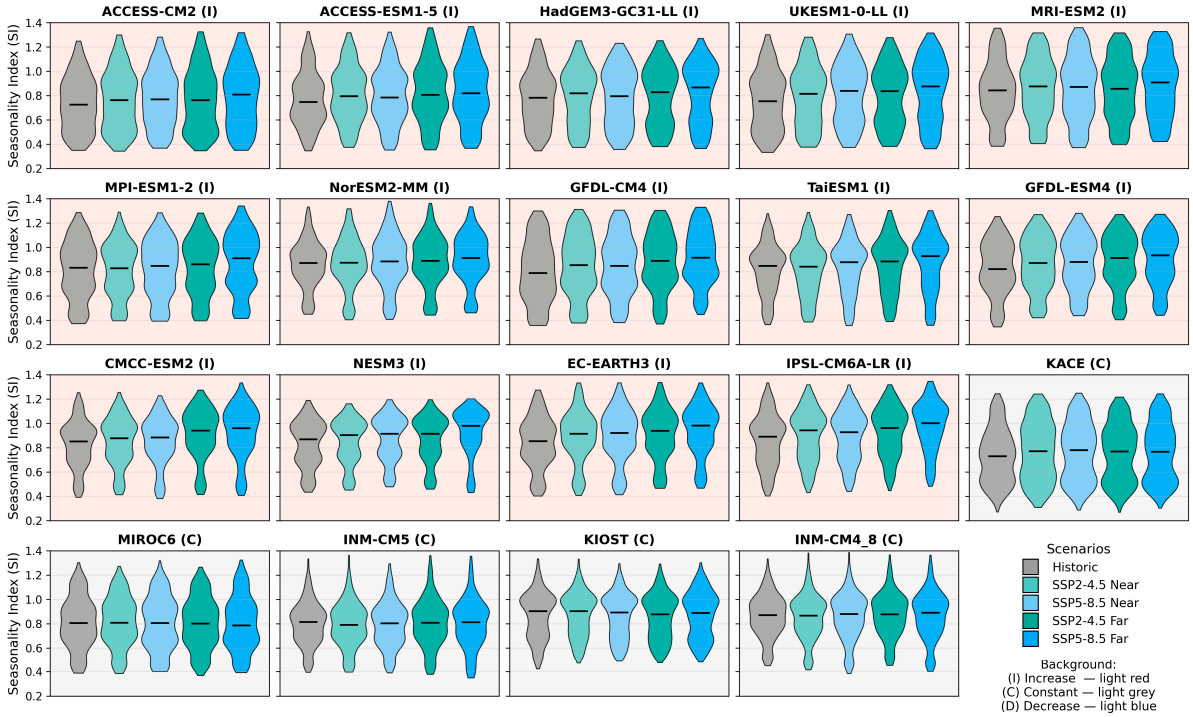

Figure 4. Seasonality Index (SI) across 19 models and 652 cities. Violin plots display the frequency of city-level temporal medians for each scenario and model, indicating the trend of the parameter for the future (increase, decrease or constant). Only constant and increasing trends were observed.

3.2. Historical Rainwater Harvesting Simulation Results

For the historical analysis, the upper (250 L) and lower (500 L) tanks were adopted as the reference configuration. Based on this setup, the potential for potable water savings

was evaluated for each building using historical climate data (Figure 5 and Table 3). Most cities exhibit saving potentials between 10% and 16%.

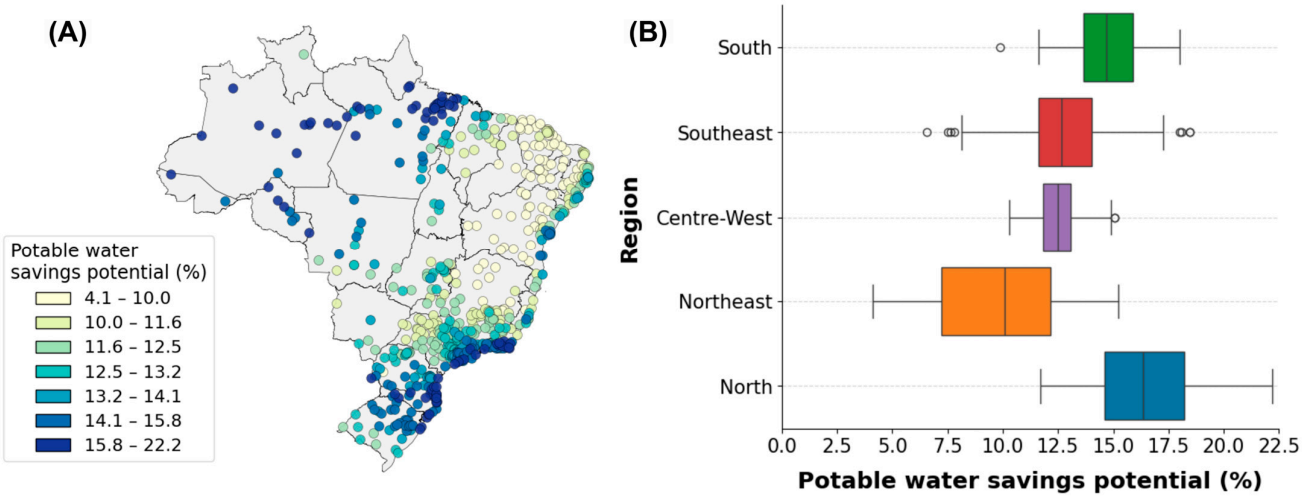

Figure 5. Average historical potable water savings potential varied across 652 cities, shown in (**A**) map and (**B**) boxplot. Circles in (**B**) represent outliers in the boxplot.

Table 3. Descriptive statistics of the average historical potable water savings potential (varied across cities and climate models).

Region	Average Historical Potable Water Savings Potential per City in Each Region (%)						
	Cities	Minimum	5th Percentile	Median	95th Percentile	Maximum	Variance
South	109	9.89	12.10	14.70	17.42	18.00	2.71
Southeast	255	6.57	10.01	12.66	16.19	18.48	3.77
Centre–West	44	10.27	10.90	12.50	14.84	15.06	1.22
Northeast	173	4.09	5.71	10.07	14.17	15.23	7.53
North	71	11.69	12.72	16.34	21.68	22.19	7.20

Figure 6 shows the average results across all cities and historical data for each state in Brazil and the six available variables. This aggregation provides an overview of local rainfall regimes and their daily dynamics at the state level. In particular, the interplay between (i) the rainfall dynamics, including Consecutive Dry Days (CDD) or Consecutive Wet Days (CWD), and total rainfall, and (ii) the rainwater harvesting system characteristics jointly determines whether inflows are effectively converted into water supply or lost as water overflow.

Figure 6A–C show the simulated mean daily rainwater use, potable water use, and rainwater overflow volume, respectively. States characterised by more frequent rainfall and/or a better intra-annual distribution tend to have higher rainwater use (Figure 6A) and, correspondingly, lower potable water consumption (Figure 6B), indicating greater potential for potable water savings. In contrast, areas experiencing long dry seasons and extended periods without rain, such as the Northeast of Brazil, typically rely less on rainwater harvesting and more heavily on potable water sources. Furthermore, in climates characterised by intense rainfall events, average rainwater overflow patterns (Figure 6C) indicate that as rainfall intensity increases, a larger proportion of the rainwater is lost once the storage capacity is reached.

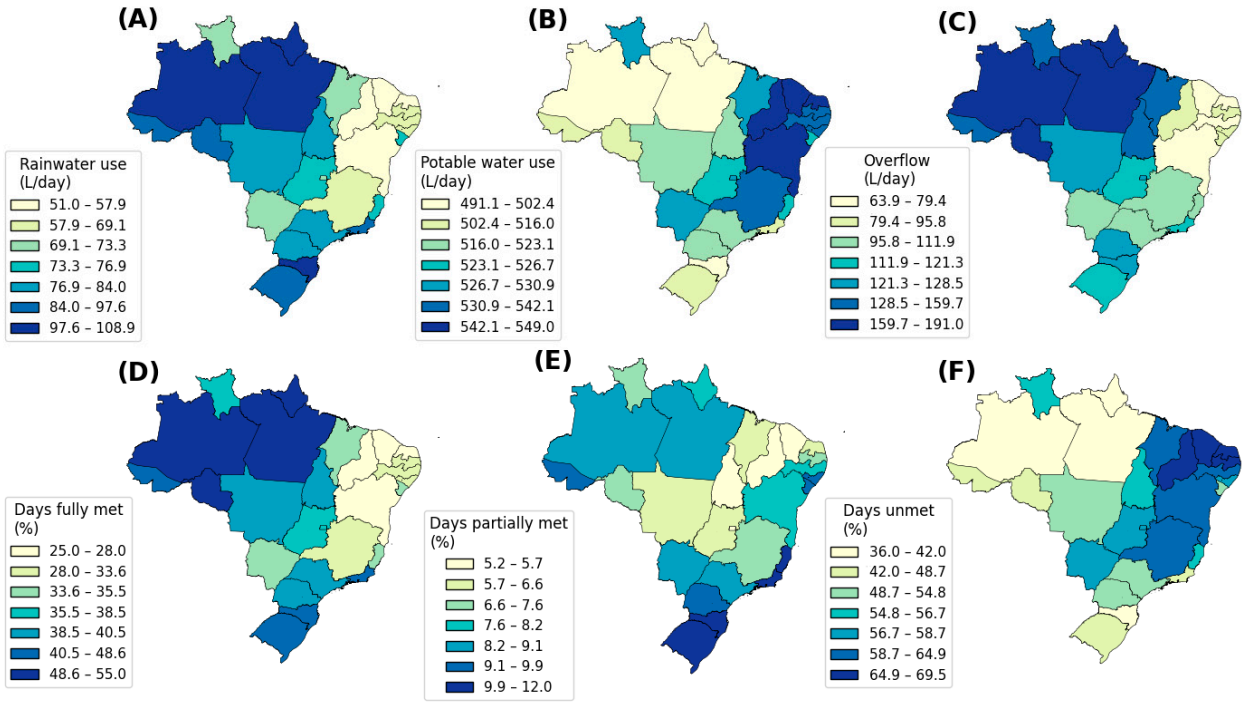

Figure 6. Average result per state, including (**A**) rainwater use, (**B**) potable water use, (**C**) daily overflow, and the percentage of days in which non-potable demand is (**D**) fully met, (**E**) partially met, and (**F**) unmet by rainwater supply.

Figure 6D–F show the percentage of days on which demand for non-potable water is entirely, partially, or not met, weighted by the number of municipalities. At most locations assessed, days on which demand is not met predominate, reflecting the persistence of dry days or insufficient capacity of the selected tanks to accumulate sufficient rainwater. Such assessment is further refined in Section 3.3. Nevertheless, the results presented reinforce that rainwater harvesting performance is linked to local rainfall seasonality and the structure of dry spells. Because potable water use compensates for unmet rainwater supply, Figure 6B,F are broadly complementary to Figure 6A,D: states with higher rainwater use and a higher share of fully met days tend to show lower potable water consumption and fewer unmet days. In wetter regimes, numeric values in Figure 6C may increase alongside Figure 6A,D, reflecting that higher inflows simultaneously raise rainwater harvesting and overflow.

The scatter plots in Figure 7 further illustrate the relationships between rainfall indices and rainwater harvesting performance. Figure 7A shows the inverse relationship between total rainfall (PRCPTOT) and the Seasonality Index, indicating that wetter locations tend to be less seasonal, while drier regions exhibit greater intra-annual variability. Figure 7B,C relate PRCPTOT to rainfall persistence, with higher rainfall associated with fewer CDD and more CWD. Consistently, higher CDD values correspond to lower potable water savings, whereas higher CWD values are associated with improved system performance due to more frequent tank replenishment. Figure 7D summarises the relationship between CWD and CDD, highlighting climatic contrasts across Brazil and their implications for rainwater-harvesting performance. It is important to reiterate that the tank sizes considered in this assessment are the 250-L upper and 500-L lower tank combination.

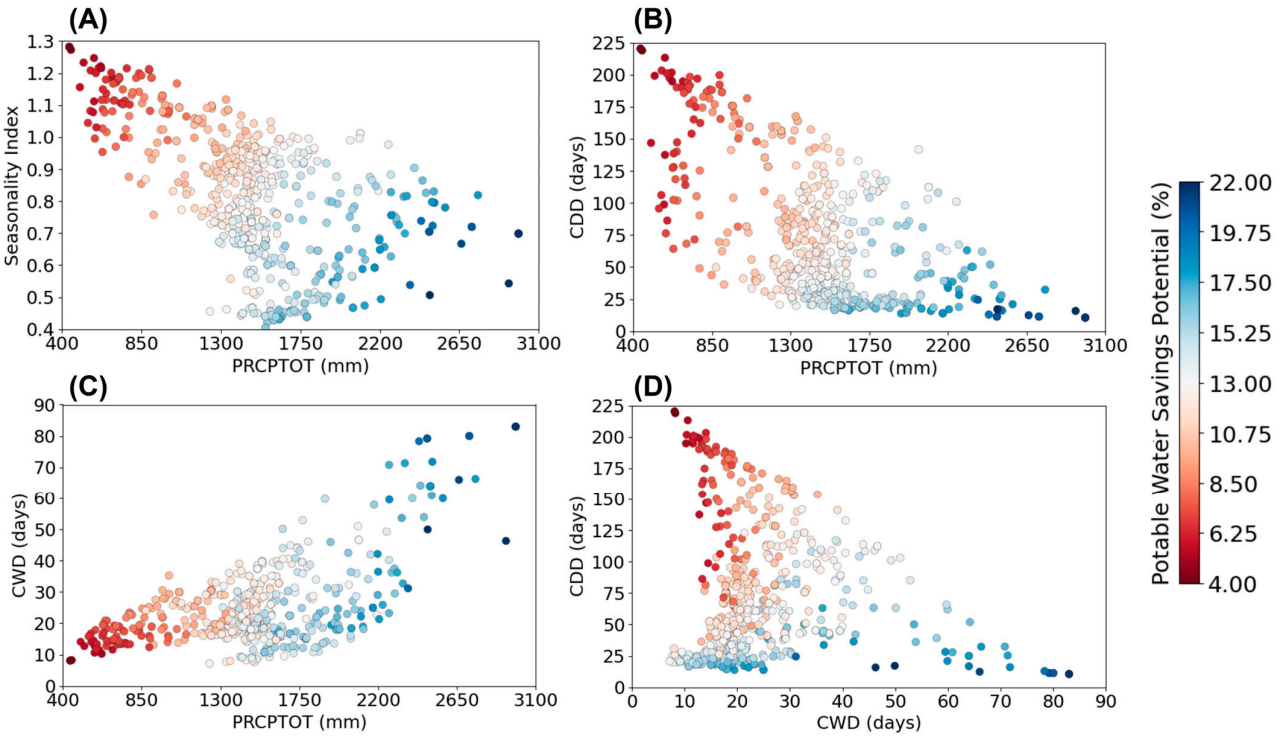

Figure 7. Scatter plot between historical (**A**) Seasonality Index and PRCPTOT, (**B**) Consecutive Dry Days (CDD) and PRCPTOT, (**C**) Consecutive Wet Days (CWD) and PRCPTOT, and (**D**) CDD and CWD, highlighting the average potable water savings potential. The assessment was performed with the 250-L upper and 500-L lower tank combination.

Regarding inter-model differences in the historical period, limited variation is expected because the CLIMBra provides bias-corrected historical simulations (1980–2013) for each CMIP6 model, using observations from Brazilian meteorological stations [48]. As this baseline is model-derived rather than observational, some residual inter-model differences may remain after bias correction. Therefore, for the historical baseline, the physical interpretation supported by Figure 7, namely the combined influence of PRCPTOT, seasonality, and the persistence of dry/wet spells on the potential for potable water savings, is more informative than minor discrepancies among climate models. This relative stability contrasts with future projections, in which shifts in seasonality and in the structure of dry and wet periods may alter these relationships and, consequently, system performance.

3.3. Future Rainwater Harvesting Simulation and Tank Sizes

Figure 8 shows the temporal evolution of the potable water savings potential averaged across all cities in each region, based on the available models. Clear regional contrasts are observed, with higher regional averages in the North and South and lower averages in the Northeast, similar to results in Figure 5. However, future changes show regional differences in trends, such as a stability or even increase in potable water savings in the South region and a decrease in the North region. Differences among climate models are also noticed, with dispersion in the regional trajectories under future conditions. The graphs are all cropped between 7.5% and 17.5%, which shows the change on a similar scale. In other words, the figure is used to compare the regions.

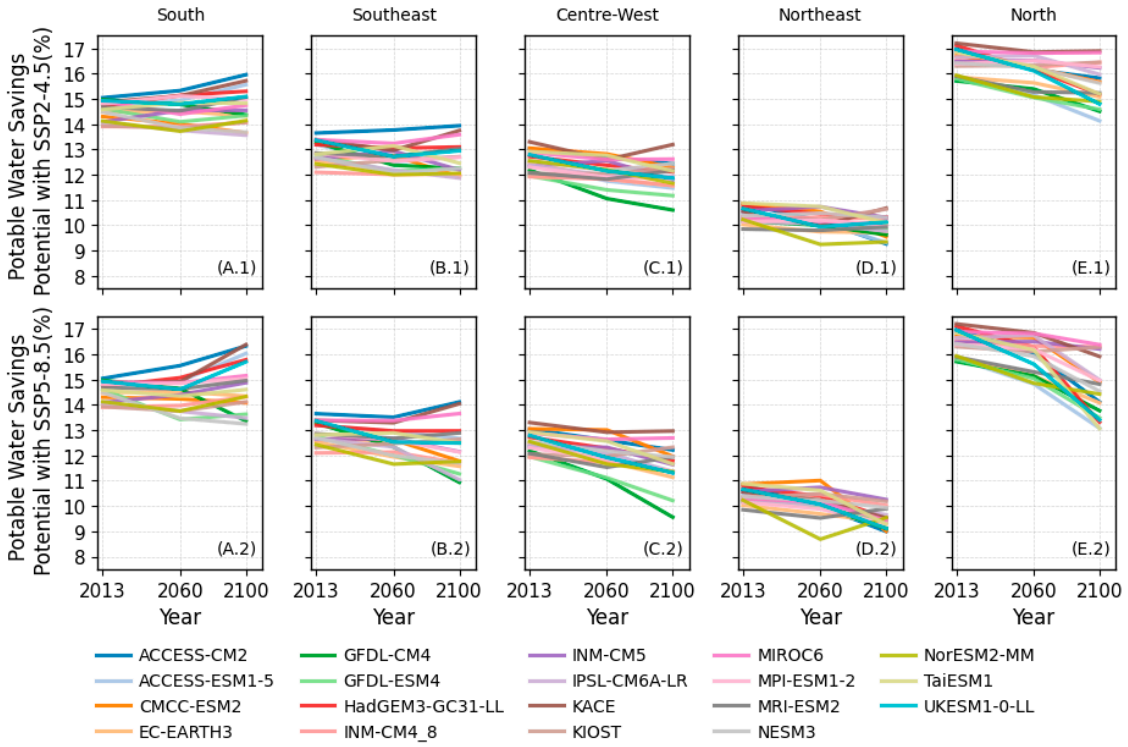

Figure 8. Lineplot between the current and future average potable water savings potential considering the different models per region (**A**) South, (**B**) Southeast, (**C**) Centre–West, (**D**) Northeast, (**E**) North and in scenarios (**1**) SSP2-4.5 and (**2**) SSP5-8.5. The assessment was performed with the 250-L upper and 500-L lower tank combination.

Table 4 shows, for each climate model, the average relative difference in the future potable water savings potential relative to the model's historical performance. Values are computed as unweighted means across the cities analysed within each region (i.e., climate location), not as population-weighted averages. Negative results indicate a reduction in savings potential (worse relative performance in the future) and positive results indicate an increase (better relative performance). The columns combine the emissions scenario and the time horizon: 2N and 2F correspond to SSP2-4.5 in the near- and far-future, while 5N and 5F correspond to SSP5-8.5 in the near- and far-future, respectively. The results are presented in relative terms, with the historical specific model performance serving as the baseline. Therefore, it provides information only on the expected change per model, not on the specific differences between models.

Figure 8 and Table 3 show a clear regional asymmetry in projected rainwater harvesting performance. Across most models, potable water savings decline in the North, Northeast and Centre–West, with the largest reductions under the SSP5-8.5 far-future scenario (5F). This pattern is consistent with increasingly intermittent rainfall and longer dry spells, which reduce tank replenishment. The Southeast shows a similar predominantly negative signal, but with smaller magnitudes and more values close to zero. The South shows the greatest inter-model divergence, with both increases and decreases, indicating uncertainty in the sign of change. Although the magnitude varies substantially across models for the same scenario–horizon combination, the direction of change is relatively consistent in the North, Northeast, and Centre–West, and least consistent in the South. This assessment is further explored in Supplementary Data S4. In summary, model dispersion increases from SSP2-4.5 to SSP5-8.5 and from the near- to the far-future horizons.

Table 4. Average relative difference between future models and historical performance (p.p. using historical data as a basis).

Model	South (%)				Southeast (%)				Centre–West (%)				Northeast (%)				North (%)			
	2N	2F	5N	5F	2N	2F	5N	5F	2N	2F	5N	5F	2N	2F	5N	5F	2N	2F	5N	5F
ACCESS-CM2	2	6	3	9	1	2	−1	3	−3	−5	−3	−6	−6	−15	−8	−17	−5	−7	−5	−17
ACCESS-ESM1-5	1	6	1	9	−5	−4	−2	−4	−5	−8	−3	−9	−3	−11	−5	−12	−4	−11	−6	−17
CMCC-ESM2	−2	−5	0	−2	1	−6	0	−7	−2	−6	0	−8	−3	−12	1	−17	−3	−6	0	−11
EC-EARTH3	0	−1	0	−1	−4	−4	−5	−8	−5	−7	−6	−11	−3	−3	−3	−7	−1	−5	−5	−11
GFDL-CM4	−1	−4	−2	−11	−7	−8	−7	−18	−9	−13	−9	−22	−2	−5	−2	−10	−2	−8	−4	−12
GFDL-ESM4	−4	−2	−8	−7	−5	−4	−6	−12	−5	−7	−7	−15	−3	−5	−3	−9	−5	−8	−5	−15
HadGEM3-GC31-LL	3	4	2	7	−1	−1	−2	−2	−3	−5	−3	−7	−3	−4	−3	−11	−6	−11	−5	−22
INM-CM4_8	0	1	0	3	−1	−1	0	−3	−1	−3	−2	−5	0	−1	1	−3	−2	−1	−1	−1
INM-CM5	3	3	2	6	2	−4	0	−4	2	−4	0	−6	2	−2	2	−3	0	−2	0	−2
IPSL-CM6A-LR	−2	−4	−2	−4	−4	−6	−3	−13	−3	−4	−3	−8	−1	−4	−1	−5	0	−4	1	−10
KACE	2	6	0	10	−3	3	−1	5	−5	−1	−3	−3	−5	1	−3	−10	−2	−2	−2	−7
KIOST	−1	1	−1	1	2	3	1	3	0	2	−1	2	−1	3	2	−1	0	1	−1	0
MIROC6	−3	−1	0	2	−1	2	0	2	−2	−2	−2	−1	−1	−2	−1	−8	0	0	0	−3
MPI-ESM1-2	2	1	0	2	−2	−1	−2	−6	−3	−4	−4	−8	1	−1	−3	−8	1	−1	−1	−9
MRI-ESM2	−1	3	0	2	−1	1	−1	0	−2	1	−5	−1	−1	1	−3	0	−4	−4	−4	−7
NESM3	−4	−6	−7	−9	−5	−4	−6	−8	−3	−1	−3	−5	1	−1	−1	−4	−1	−5	−3	−11
NorESM2-MM	−3	0	−3	1	−3	−3	−6	−5	−3	−7	−7	−10	−10	−9	−15	−7	−5	−7	−7	−9
TaiESM1	2	2	−2	0	3	−3	1	−3	−1	−6	−3	−10	−1	−7	−2	−15	−3	−10	−4	−22
UKESM1-0-LL	−1	1	−2	5	−5	−3	−6	−7	−5	−7	−7	−12	−7	−5	−6	−15	−5	−13	−8	−21
Models' average *	0	1	−1	1	−2	−2	−2	−4	−3	−5	−4	−8	−2	−4	−3	−9	−2	−5	−3	−11

Notes: 2N is SSP2-4.5 near future; 2F is SSP2-4.5 far future; 5N is SSP5-8.5 near future; 5F is SSP5-8.5 far future. Note: The values indicate the decrease or increase in potable water-saving potential, with the reference system (historical) set to 100% performance. Thus, normalisation is performed using the model's original value. If the average potential for potable water savings in the South region was 20%, the 6% increase yields a new percentage of 21.2% (+1.2 percentage points in absolute values). In other words, this table presents relative values, normalising the visualisation between models. For absolute changes in the potable water savings potential, see Figure 9 and Supplementary Data S3. Observation: the tank sizes considered here are the 250- and 500-L combination. * An average of the columns in the table is provided in a final line, representing the average relative change among the climate models. The colour scheme was provided so that red indicates a decrease and blue an increase, with white indicating no expected variation.

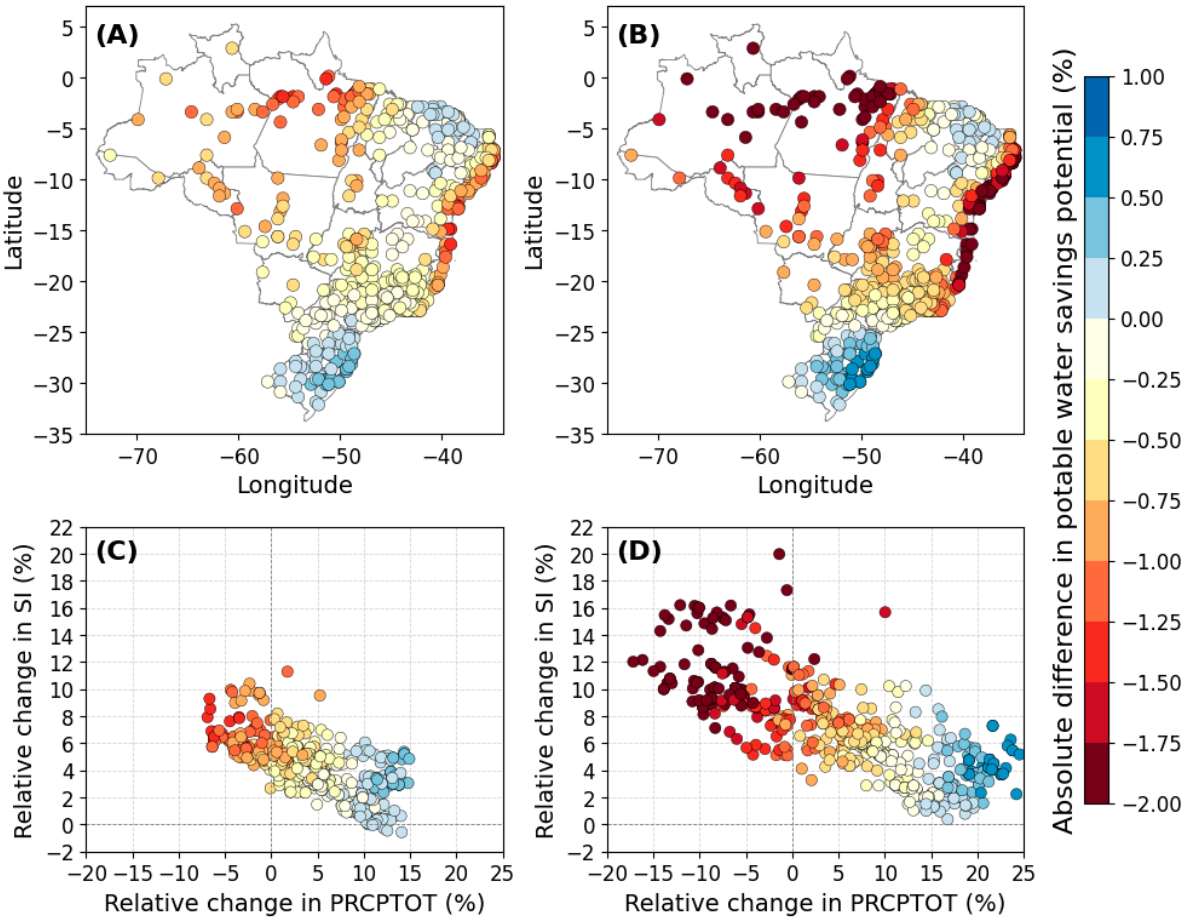

Figure 9. Absolute change in the potable water savings potential shown in (**A**) a map with SSP2-4.5 far-future versus historical average, (**B**) a map with SSP5-8.5 far-future versus historical average, (**C**) a scatterplot with relative changes in seasonality index and PRCPTOT considering SSP2-4.5 far-future, and (**D**) a scatterplot with relative changes in seasonality index and PRCPTOT considering SSP5-8.5 far-future.

Figure 9 shows the difference in the far-future water-savings potential relative to historical data, highlighting spatial and regional patterns. In SSP2-4.5, changes tend to be more moderate, whereas in SSP5-8.5, more intense and widespread changes predominate, particularly in the northern and northeastern states. These larger changes occur in PRCPTOT, SI, and the potable water savings potential, highlighting the connection between future rainfall patterns and rainwater harvesting performance.

Figure 9 also highlights the dispersion of results, indicating differences associated with inter-state spatial heterogeneity. Data are averaged across models, which masks differences in model projections; Supplementary Data S3 shows changes in each model separately. In Figure 9C,D, positive percentages indicate an increase in the index, whereas negative percentages indicate a decrease. Consider the relative changes in the seasonality index and PRCPTOT, rather than their absolute values. However, consider the absolute change in the potable water savings changes (i.e., the colouring scheme). See that a change in −2% in absolute difference can represent −20% of relative change in an original 10% potable water savings potential. Additionally, these values are averaged in the figure.

In addition to assessing the impacts of climate change on the performance of rainwater harvesting systems, we explored how tank definition influences performance. Figure 10 shows the curves of potable water savings potential as a function of the total rainfall volume reserved (i.e., the sum of the lower and upper tank sizes) for each region of the country.

The median across the models was used to mitigate the effects of rainfall outliers. Further details on inter-model variation are provided in Supplementary Data S4.

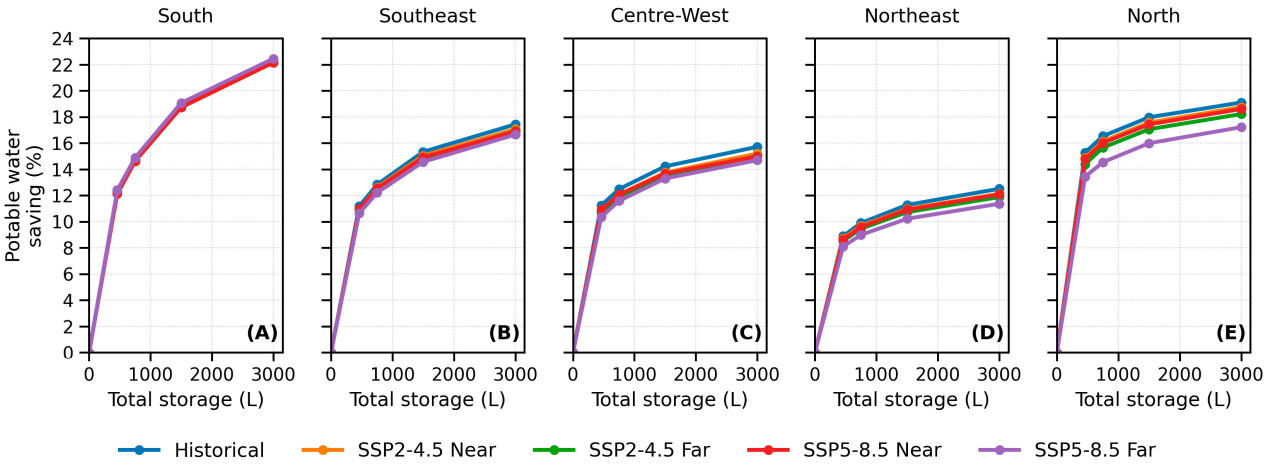

Figure 10. Average potable water savings potential in different scenarios and tank sizes (total storage refers to the sum of the upper and lower tank capacities in L), averaged among cities considering the median of the climate models for the (**A**) South, (**B**) Southeast, (**C**) Centre–West, (**D**) Northeast, and (**E**) North regions.

It can be observed that the choice of tank has a greater influence in places with higher rainfall, indicating that interspersed dry days are supplied by stored rainwater. Dry places may not benefit substantially from larger tank capacities, as they would require higher levels of rainwater harvesting and storage, which are often not feasible given the small catchment area. In summary, the climate scenario has a lesser effect on performance than the tank sizes. Supplementary Data S5 presents the same results through a global sensitivity analysis, indicating that tank sizes are more influential in explaining the variance.

3.4. Impact on Overflow

At last, Figure 11 summarises the average daily overflow associated with each lower–upper tank combination, considering all cities, both emissions scenarios, and regional aggregation across Brazil. The median across the models was used to mitigate the effects of extreme rainfall outliers.

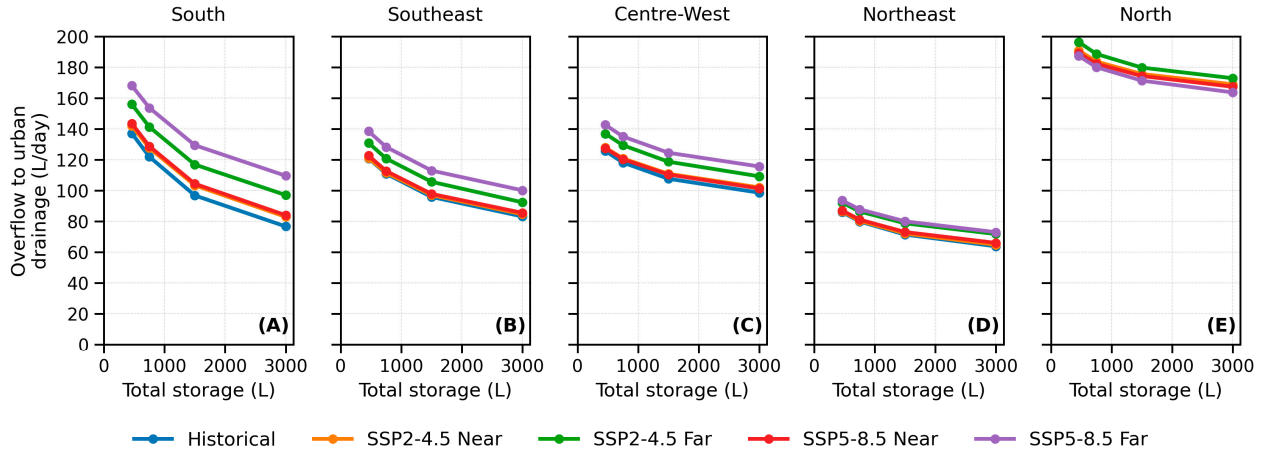

Figure 11. Daily rainwater overflow to drainage in different scenarios and tank sizes (total storage refers to the sum of the upper and lower tank capacities in L), averaged among cities considering the median of the climate models for the (**A**) South, (**B**) Southeast, (**C**) Centre–West, (**D**) Northeast, and (**E**) North regions.

In the historical period, the increase in storage capacity from a low capacity (310 L lower and 150 L upper) to a high capacity (2000 L lower and 1000 L upper) reduces the average overflow volume in all Brazilian regions, with reductions ranging from 22.1 L/day in the Northeast to 60.4 L/day in the South. Under the SSP5-8.5 far-future scenario, this trend persists, with reductions of 20.6 L/day in the Northeast and 58.5 L/day in the South, indicating that the increase in stored volume continues to influence overflows. However, in the North and Northeast regions, differences in overflow across the scenarios are very small, unlike in the other regions. These factors show that the variables "tank size" and the "future scenario" present different levels of impact on overflow across regions of Brazil.

4. Discussion

4.1. Robust Feasibility Assessment Under Climate Change

Changes in rainfall amount and temporal distribution affect the use of rainwater in buildings. Instead of a single value, it is more appropriate to consider a set of possible outcomes. This framework aligns with international assessments. In general, studies show that climate non-stationarity and uncertainty between scenarios and models widen the plausible range of reliability. Thus, interpretation should be based on risk rather than on a single deterministic estimate [41,74–76].

Historically, Brazil has shown strong spatial heterogeneity in rainfall data. This variation reflects the morphology and climatology of a country on a continental scale. In line with previous studies [9,12,77], higher rainfall is observed in the South and North regions, and lower rainfall in the Northeast, with Centre–West and Southeast regions with intermediary values. It is therefore expected that the greatest potential for potable water savings will occur in wetter areas with less temporal rainfall variability, while the lowest potential will be in drier, more seasonal areas. The historical analysis presented in Figure 5 corroborates this hypothesis.

In this heterogeneous context, future projections indicate divergent regional responses. Figures 3 and 4 and Supplementary Data S3 show a generalised increase in the seasonality index across most of the country, suggesting a more irregular distribution of rainfall events and longer dry periods between them. In contrast, the projected changes in total annual rainfall are not uniform across the region. There are reductions along the northeast coast and in parts of the Amazon region, while increases are expected elsewhere in the territory. Some regions, such as southern Brazil, are consistent with the analysis by Carvalho et al. [78], which finds that increased annual rainfall, combined with greater seasonality, indicates an increase in future extreme events, with more intense rainfall concentrated in a short period.

However, comparisons between climate models reveal significant differences in future rainfall characteristics among possible projections. Furthermore, Supplementary Data S4 shows that agreement among models is not uniform across the territory. There is greater robustness in the Centre–West, North, and coastal areas of the Southeast and Northeast. In contrast, the South and parts of the Northeast show less consensus on the direction and magnitude of change, warranting caution in interpreting and using these results for planning decisions.

From a decision-making perspective, the assessment of rainwater harvesting systems should be based on local rainfall patterns, but, whenever possible, consider a set of plausible climate scenarios and data dispersion. Instead of interpreting climate impacts as deterministic changes, results should be reported as performance envelopes, which leads to more robust decisions than those based on a single historical projection. International assessments of rainwater harvesting under climate change also recommend reporting distributions and robustness across scenarios and models to support decisions, considering uncertainties, rather than treating future performance as a point estimate [74–76].

4.2. Design Implications on Tank Sizing

Before discussing the design implications, it is important to explain why tank sizing is critical. The sensitivity analysis at the local scale (by city), presented in Supplementary Data S5, indicates that tank volume accounts for the largest share of the variance in results, surpassing the influence of the climate model and emissions scenario. This result reinforces that, in project practice, resizing is the main controllable variable for managing risk and adjusting system performance in the face of future climate uncertainty.

As shown in the relationships between volume and performance (Figures 10 and 11), increasing storage volume can reduce potable water demand by expanding system capacity, ultimately reaching a performance limit. However, climate change can reduce or increase system reliability by altering rainfall variability and event sequences [41]. Studies that incorporate climate projections show the same pattern. Therefore, sizing should be assessed under future climate uncertainty, rather than under the assumption of stationarity [34,37,74–76]. In regimes with strong seasonality or water limitations, increasing storage may yield diminishing returns when replenishment becomes the limiting factor; thus, resizing should be treated as a conditional adaptation measure rather than a general rule [41,65].

Spatial patterns in Brazil indicate that resizing does not work the same way in all cities. Where there is a tendency towards higher annual rainfall and lower seasonality indices, larger volumes tend to maintain rainwater demand and reduce the risk of performance decline in different projections. However, where water scarcity and expected performance deterioration are greater (Supplementary Data S3), increasing the tank volume may not be sufficient. In these locations, it may be necessary to review water service levels and consider hybrid solutions that combine storage with supply- and demand-reduction strategies. Where projected changes are small or models diverge more, resizing can support risk management. In these cases, corroborating Alamdari et al. [41], the goal should be to use reliability indicators under future climate conditions to support design decisions.

Although this study does not include a cost analysis, increasing the tank volume has direct implications for initial investment, space requirements, and maintenance. The attractiveness of resizing depends on whether the marginal gains in water savings justify the additional cost in each future rainfall regime [65]. Furthermore, the tariff structure conditions consumption and, consequently, the economic return of these measures. Thus, connections between the system cost, the tariff structure, climate change, and economic changes are conditioned by the climate and future uncertainties [79]. Finally, simulations and projections should also be evaluated in the context of larger buildings, such as public and commercial buildings, as well as other types that tend to use larger tank volumes. Under these conditions, other analyses, discussions and conclusions can be obtained to aid decision-making, given the climate change outlook and uncertainties.

4.3. Risks Associated with Water Shortage or Overflow

Future changes in rainfall pose two risks to rainwater harvesting systems: water scarcity and overflow [41,74,75]. The results indicate that the risk of scarcity increases as rainfall becomes more intermittent, when dry periods are prolonged or effective recharge decreases. As a consequence, the system loses its capacity to meet non-potable demand. These mechanisms have already been noted in international assessments of the impacts of climate change on the reliability of rainwater harvesting [41,74,75]. In this research, the risk tends to be more robust when several models converge on a negative performance signal. This was most evident in scenarios with higher emissions and in the long term. However, it should be noted that this variation was much lower than that observed in the choice of city within the country and in the tank volume, highlighting the connection between the variables (Supplementary Data S5).

The risk of overflow involves a distinct mechanism. When rainfall becomes more concentrated in fewer events, the probability of tank saturation increases. In this context, a larger tank can reduce overflow by providing greater storage capacity, but this benefit is conditional and may diminish when antecedent conditions keep the tank partially full. Furthermore, overflow volumes are not direct evidence of downstream flooding, as they depend on urban micro- and macro-drainage conditions. Therefore, assessing peak flow mitigation under future extreme conditions is an important step. However, this is beyond the scope of the daily water balance adopted in this study. In general, event-based hydrological–hydraulic modelling is necessary to quantify impacts on drainage and detention performance in short-duration extremes [80].

In addition to performance at the building scale, the projected increase in risks associated with water scarcity and flooding has broader social implications. As rainwater harvesting systems become less reliable under future rainfall regimes, households and facilities are likely to rely more on the potable water network, which could amplify seasonal demand peaks and increase system stress during periods of greater drought risk. In practice, this may deepen inequalities in adaptive capacity: higher-income users may compensate by investing in greater storage, alternative sources, or renovations, while lower-income households may be disproportionately vulnerable to service interruptions and price pressures. In general, climate-based rainwater harvesting strategies should be aligned with integrated neighbourhood-scale stormwater management strategies [80–82].

4.4. Policy and Planning Relevance in Brazil

Created in 2003 and regulated in 2013 (Law No. 12873/2013), the Brazilian Cisterns Programme was designed to provide low-income families with access to more quality water [83]. It began with the installation of one million rainwater harvesting systems with fixed-volume tanks of 10,000 L in the North-Eastern region. This public policy, for example, could benefit from an assessment of future climate conditions to mitigate the risk of water supply failures among beneficiary households. Because system performance is strongly influenced by rainfall patterns and seasonality, simulations using historical data and future climate models could be used to predict operational metrics, such as the number of days in which the system is not operational.

Climate change also puts pressure on centralised systems by prolonging droughts, increasing variability and intensifying floods, affecting existing infrastructure [11]. In this scenario, the debate on the integration between centralised systems and alternative sources becomes essential. For Brazilian water policy and programmes, this reinforces the need to treat rainwater harvesting as part of an integrated water security strategy, linked to demand management and drainage planning, rather than as an isolated measure.

International studies discussing rainwater harvesting in future climates have increasingly framed decentralised solutions as components of urban water resilience [35–41]. In this sense, rainwater harvesting, including collective arrangements, can add a layer of resilience by reducing demand on the centralised system and mitigating periods of water stress. It is, therefore, a solution that advances not only for the individual context but also for the collective. However, its effectiveness remains uncertain and requires assessments under future rainfall patterns, with transparency of results, making scenarios, horizons and inter-model uncertainty explicit, as recommended in recent assessments [36,37,41]. The results of this study indicate the direction of climate models across Brazil, without excluding the need for local assessments for adequate water resource management planning.

4.5. Limitations and Future Studies

This study has limitations that should be acknowledged to support transparent interpretation of the findings, as follows. Rainwater harvesting was simulated in Netuno using an intermediate YBS/YAS formulation and a daily mass balance. Although suitable for comparative analyses, this structure may smooth out operational differences and fails to represent sub-daily dynamics (e.g., rapid tank filling and overflow during short, intense storms). Furthermore, Netuno does not model evaporation losses from storage, which may slightly overestimate stored volumes and potable water savings, especially in warmer and drier regions.

Secondly, the results incorporate the uncertainties of the climate dataset. Despite bias correction and the use of a CMIP6 multi-model ensemble, daily resolution and 0.25° regridding may smooth out localised extremes. The generalisation of the study to other types of buildings is also limited by the use of a single housing archetype, which prevents inferences about the Brazilian building or housing stock. In sequence, the roof runoff coefficient and first-flush disposal were assumed constant, without testing climate-adaptive strategies such as alternative materials or collection technologies. This limits the assessment of how quality protection measures and system performance may change under non-stationary rainfall regimes. Finally, the study did not assess financial viability (life cycle cost, payback, accessibility constraints, or tariff benefits) and, therefore, the results should be interpreted as hydrological and performance implications, not as investment recommendations.

Building on these constraints, future studies may:

- Incorporate additional archetypes and variability in roof area, occupancy, end-use patterns, and non-potable demand, including tariff structures and affordability constraints;
- Complement mean overflow with risk-oriented indicators and, where feasible, couple rainwater harvesting outputs to hydraulic routing to better link overflow to drainage-system impacts;
- Use sub-daily or event-based rainfall inputs to improve representation of short-duration extremes relevant to overflow; and
- Integrate decentralised rainwater-harvesting performance with projections of centralised water-supply availability and reliability to support multi-scale assessments of urban water resilience under climate change.

5. Conclusions

Rainwater harvesting is highly dependent on climate and should not be treated as a stationary resource. The CMIP6 multi-projection assessment indicates that plausible changes in rainfall regimes can alter both potable water savings and overflow indicators. The results were spatially heterogeneous and tended to vary more in the most extreme scenarios and over longer time horizons. Thus, the main conclusion is not a single, deterministic pattern, but rather an asymmetric regional response to climate change, with results varying between models. In this context, the interpretation must go beyond the set's averages and explicitly incorporate agreement among the models, as this indicates where the projected signal is most robust and where the uncertainty is greatest. Therefore, the conclusions should be communicated as performance ranges (central tendency and dispersion) and accompanied by measures of inter-model consistency, rather than as point estimates.

Tank resizing is a context-dependent adaptation option rather than a universal solution. Its potential benefits should be assessed against local hydroclimatic controls and ensemble uncertainty. Increased storage tended to improve savings and reduce mean overflow, mostly where rainfall remains sufficient and intermittent enough to recharge the system.

In contrast, in rainfall-limited locations, the benefits of larger tanks diminished because additional storage capacity could not compensate for insufficient rainfall.

From a practical standpoint, the proposed method supports performance-oriented dimensioning by reporting future climates for multiple models, scenarios, and horizons, while also highlighting areas of greatest agreement between models. Overflow indicators should be interpreted only as daily overflow volume, without inferring peak flows or flood impacts, which require event-based hydrological-hydraulic modelling. In summary, the research provides guidance on what to expect in each region and supports guidelines based on performance and risk ranges; however, it does not replace local assessments, which are necessary for planning and decision-making in specific contexts.

Finally, it is important to note that future climate scenarios and models had less impact on the potential for potable water savings than did variations in interstate rainfall patterns, demonstrating that these factors are important for the design and performance of rainwater harvesting systems. The future climate also has less impact than differences in tank volumes. It is understood that the climate will change and that this change will affect system performance, but it is important to realise that the current structure for defining systems and national differences already indicates a greater emphasis on effectiveness. In summary, proper sizing of rainwater harvesting, considering local characteristics, expected performance, and potential rainfall patterns, is key to the system's effectiveness.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18070792/s1, Table S1: Demographic data on all the cities assessed—This table is made available in an Excel file; Supplementary Data S1—Study sample and spatial coverage; Supplementary Data S2—Distribution of PRCPTOT in CMIP6 models; Supplementary Data S3—Future versus historical results considering 250/500-L tanks; Supplementary Data S4—Inter-model agreement on simulation results (SNR and sign agreement); Supplementary Data S5—Sensitivity analysis of the simulation results; Supplementary Data S6—Linear regression of potable water savings versus rainfall data.

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