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Building resilience in the Global South: Evidence from a decentralized water policy in Brazil

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ABSTRACT

Climate change poses increasing risks to population well-being through heightened water scarcity. This threat is particularly pronounced in low-income and climate-vulnerable regions, where traditional water infrastructure may not be feasible in the near term. This study evaluates the effectiveness of a decentralized water policy as a climate adaptation strategy, focusing on Brazil's Cisterns Program, a large-scale rainwater harvesting initiative designed to build climate resilience in remote, underserved communities. The analysis shows that access to rainwater harvesting reduces severe cases of waterborne diseases by approximately 34%. Beyond these average health gains, the study assesses climate resilience by examining how the program moderates the impacts of drought shocks. Using multiple definitions of drought, the analysis shows that these events substantially increase disease burden. However, these adverse effects are significantly mitigated or fully offset by the program, indicating a sharp reduction in vulnerability to climate-related stress. Evidence on mechanisms suggests that effectiveness depends not only on water availability but also on beneficiaries' capacity to manage water safely and on program implementation. Impacts are significantly larger in more educated communities and where local civil-society organizations play a central role in implementation. These findings highlight the potential of low-cost, decentralized interventions as viable climate adaptation strategies, particularly in settings where large-scale infrastructure projects are impractical, and offer a scalable model for resilience-building development policies in the Global South.

1. Introduction

Access to water is a fundamental human right, yet nearly 27% of the global population, or more than 2.2 billion people, lack regular access to safely managed drinking water services. This issue is particularly severe in rural areas, where 80% of those without reliable water sources reside, and in low-income countries, which often lack the resources to invest in water, sanitation, and hygiene (WASH) infrastructure (WHO/UNICEF, 2024). Consequently, waterborne diseases remain a significant health threat in the least developed countries, particularly in regions with limited access to healthcare (e.g., Gamper-Rabindran et al., 2010; Kremer et al., 2011; Mattioli et al., 2014; Duflo et al., 2015; Garg et al., 2018). Climate change is expected to worsen access to clean water for populations already facing frequent extreme events, such as droughts and floods, thereby increasing the burden of climate-related diseases (e.g., Funari

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et al., 2012; Semenza, 2020).[1] These facts highlight the need for affordable interventions that reach underserved populations, particularly in remote, impoverished settings, while fostering adaptation and resilience (e.g., Smith et al., 2015).

In this study, I explore the well-established link between water scarcity and waterborne diseases (e.g., Jofre et al., 2010) to evaluate the effectiveness of a decentralized climate adaptation intervention focused on low-income households living in isolated areas. Specifically, this study examines whether a relatively low-cost rainwater harvesting (RWH) technology, originally developed by grassroots organizations, can serve as a viable strategy for low-income countries or communities that often lack the resources to afford large-scale infrastructure projects. It also evaluates whether such systems strengthen climate resilience in regions exposed to recurring shocks, providing evidence on their potential as climate adaptation strategies. Although RWH is increasingly recognized as a potentially scalable approach for expanding access to safely managed drinking water, particularly in resource-constrained environments, rigorous empirical evidence on its effectiveness at scale and its value as a climate adaptation strategy remains limited (Yuan et al., 2025).

The One Million Cisterns Program (P1MC), hereafter the *Cisterns Program*, is a large-scale initiative aimed at mitigating water scarcity for low-income households, particularly in rural areas where improved water sources are scarce and building public water connections are prohibitively expensive. The program implements various *social technologies* – low-cost, locally developed micro-interventions – designed to help households and communities capture, store, and manage water from multiple sources. Its largest component, the *First Water Program*, focuses on installing RWH systems for human consumption mainly in Brazil's Semiarid region, aiming to enhance resilience to prolonged dry seasons and recurring droughts.

The *Cisterns Program* has garnered significant attention from both domestic and international organizations and has received numerous awards in recognition of its innovative approach to increasing water availability and resilience for populations vulnerable to irregular rainfall and climate shocks.[2] As the program gained international recognition, its model began to be exported from Brazil to other developing countries. For example, the World Food Programme supports projects in Benin, Tanzania, and Mozambique based on the Brazilian experience.[3] Similarly, in 2018, the Food and Agriculture Organization of the United Nations (FAO) launched the "One Million Cisterns for the Sahel" Initiative with the declared goal to bring the Brazilian experience to this region.[4] Meanwhile, various non-governmental organizations develop their own strategies based on the Brazil's Cisterns Program.

Unfortunately, the enthusiasm surrounding this type of decentralized, self-contained initiative has not been matched by rigorous evaluations of its effectiveness. In fact, very few studies have explored the causal effects of such interventions on key development outcomes. More specifically, only three studies have examined the program's impacts using rigorous methods for causal inference. However, these studies only tangentially address the intervention's performance under climate stress, as assessing climate resilience was not their primary objective.

The results indicate that the program is an effective intervention for improving both welfare and resilience. First, a difference-in-differences strategy leveraging the program's rollout shows a reduction of 176 hospitalization cases per 100,000 residents due to acute diarrheal infections, an approximate 34% decrease relative to the sample average. Additionally, an analysis of the impacts of exogenous extreme shocks on waterborne diseases reveals that droughts significantly worsen health outcomes, increasing cases by 47 to 77 per 100,000 residents, depending on the shock's definition, severity, and model specification. More importantly, the program consistently mitigates the adverse effects of drought shocks, often fully offsetting them, underscoring its effectiveness as an adaptation strategy.

Finally, I use household-level data to explore the potential mechanisms driving the observed results, drawing on the WASH literature and studies of the Cisterns Program. The analysis suggests that the program's positive effects are amplified in areas with more educated beneficiaries and where local NGOs are actively involved in the program's implementation. Collectively, these findings indicate that the program enhances households' control over water resources, enabling beneficiaries to prevent contamination more effectively and pointing to the critical role of agency in determining the program's success.

These findings contribute to the growing literature on climate adaptation in developing countries by demonstrating the potential of rainwater harvesting (RWH) as a scalable solution. The study provides a comprehensive, population-level evaluation of the Cisterns Program that goes beyond the localized impacts documented in prior work. Rather than focusing on specific subgroups or short-run outcomes, it examines whether the program generates measurable improvements in community-wide health and whether these gains persist under adverse climatic conditions. By explicitly analyzing how health outcomes respond to drought shocks, the study offers direct evidence on whether decentralized RWH functions as an effective climate adaptation policy, rather than an intervention whose benefits are confined to normal periods.

[1] Despite growing evidence placing climate change as the greatest health threat to humanity, most countries have yet to integrate climate risk considerations or climate resilience into their WASH policies (WHO, 2022).

[2] Some of the awards received by the program include: (i) the 2017 Future Policy Award from the World Future Council in partnership with the United Nations Convention to Combat Desertification (UNCCD); (ii) the 2009 SEED Award for Entrepreneurship in Sustainable Development, granted by the United Nations Environment Programme (UNEP), the United Nations Development Programme (UNDP), and the International Union for Conservation of Nature (IUCN); (iii) the 2008 Josue de Castro Award for Best Practices in Food and Nutrition Security Project Management in the Civil Society category; (iv) the 2006 National Water Agency (ANA) Award in the Rational Use of Water Resources category; and (v) the 2005 Millennium Development Goals (MDG) Award, sponsored by the UNDP.

[3] The initiative is part of the larger Beyond Cotton Project. For more information see https://centrodeexcelencia.org.br/en/cisternas-tecnologia-brasileira-mudando-vidas-na-tanzania/(retrieved on August 16, 2024).

[4] Senegal, The Gambia, Cape Verde, Niger, Burkina Faso, Chad, and Mali were selected as pilot countries for the initiative. For more information, see https://openknowledge.fao.org/items/5f284ccd-61b0-4f94-8715-c2f3bd97b925 (Retrieved on August 16th, 2024).

The article is organized as follows: Section 2 provides an overview of the literature on rainwater harvesting and decentralized water interventions, situating the Cisterns Program within this broader context and highlighting the study's main contributions. Section 3 provides background information on the geography and socioeconomic characteristics of Brazil's Semiarid Region, along with an overview of the Cisterns Program. Section 4 presents the data sources, summary statistics, and empirical strategies. Section 5 reports the main findings and robustness checks, divided into two parts: Section 5.1 presents the results of the impact evaluation, while Section 5.2 analyzes the resilience-building dimension. Section 6 investigates potential mechanisms, drawing on the WASH and rainwater harvesting literatures. Section 7 provides a back-of-the-envelope cost-benefit analysis to assess the program's viability. Section 8 concludes.

2. Related literature and contributions

Rainwater harvesting (RWH) is a common practice that has gained renewed attention as a decentralized alternative to piped infrastructure in water-scarce settings (e.g., Lee and Visscher, 1990; UNICEF Brazil, 2017). Although RWH systems can supply a substantial share of household potable water needs under appropriate climatic and social conditions (Musayev et al., 2018), their potential as a large-scale solution remains largely untapped. Recent global evidence emphasizes this gap: 88% of those lacking safely managed drinking water live in regions with abundant precipitation, yet only a small fraction (1.3%) relies on rainwater for potable use. Estimates suggest that expanded RWH deployment could increase access to safely managed water by up to 26%, benefiting up to two billion people (Yuan et al., 2025). Until Brazil's Cisterns Program, however, no country had implemented RWH as a scalable national intervention (Tavares et al., 2009).

When the Cisterns Program became a policy priority in Brazil, it sparked debates over its design and effectiveness. Studies on the program's governance often highlight its bottom-up nature (e.g., Andrade et al., 2012), suggesting this feature could make the program outperform the usual top-down *ad hoc* projects implemented in the region, often marred by corruption scandals and limited impact (Lemos, 2007).[5] The works focusing on the program's effectiveness, however, reveal a more nuanced picture. While some studies indicate a significant reduction in waterborne diseases among households with cisterns (Fonseca, 2012; Marcynuk et al., 2013; Barros et al., 2013; Fonseca et al., 2014; Bezerra de Sousa et al., 2017), others found that although cisterns initially provided high water quality, improper handling could introduce contaminants and undermine water safety (Amorim and Porto, 2001; Brito et al., 2005b; Luna et al., 2011; Alves et al., 2014). This may explain why Heller et al. (2012) found no significant difference in disease burden between households with and without cisterns.

These earlier evaluations were typically based on cross-sectional data or *in situ* surveys that primarily gathered beneficiaries' *perceptions* in a few sites. While they offer valuable insights into the program's implementation and potential benefits, their design limits the ability to draw causal inferences or to evaluate the program's effectiveness over time in a systematic or generalizable way.

More recently, a growing body of work has sought to address these limitations using experimental and quasi-experimental approaches. Silva, 2015 is likely the first to adopt a causal framework to estimate impacts on infant mortality from acute diarrheal diseases. The study finds that, after nine years of exposure, treated municipalities experienced mortality reductions of up to 69%.

Building on this evidence, Da Mata et al. (2023) show that access to cisterns during pregnancy increases birth weight, a critical indicator of newborn health with long-term developmental repercussions. Their results align with broader research linking access to clean water with improved maternal and child health outcomes. However, probably due to data limitations, the study could not extend its analysis to other potentially affected groups, such as children and the elderly, who may also experience significant benefits from the intervention.

Finally, Bobonis et al. (2022) conducted a randomized controlled trial (RCT) to evaluate the impact of cistern installation across 40 municipalities of the Brazilian Semiarid. Their findings indicate a reduction in economic vulnerability among low-income households, accompanied by a decline in clientelist exchanges, thereby reinforcing and quantifying previously hypothesized effects of the program on governance.[6]

This study expands on previous evaluations of the Cisterns Program in several ways. First, it provides a comprehensive, population-level assessment of the program's welfare impacts, leveraging recent advances in the difference-in-differences literature to address challenges in causal identification under staggered implementation. Second, it captures the broader burden of severe waterborne diseases and examines heterogeneity in impacts across demographic groups (e.g., children and older adults). Using long-run administrative health data, it estimates both average treatment effects and variation by demographic and implementation characteristics, offering a more complete picture than earlier evaluations. Third, it builds on earlier assessments of mechanisms to highlight how knowledge, agency, and local conditions shape program effectiveness. Finally, and most importantly, the study introduces a climate

[5] Created by grassroots movements, the Cisterns Program adopted a bottom-up approach, actively involving beneficiaries in the process. This participatory dynamic allowed the program to adapt to the realities of local populations, potentially empowering beneficiaries while mitigating exclusionary dynamics at the local level. For example, implementation evaluations indicate that the program amplified women's voices and gave communities a role in local decision-making (Nogueira et al., 2020; Nogueira, 2017; Pereira, 2016).

[6] The provision of private benefits by government officials and political parties in exchange for votes is notably prevalent in Brazil's Semiarid region and has been associated with various detrimental effects on development (Lemos, 2007; Bedran-Martins and Lemos, 2017b). According to Bobonis et al. (2022), medicines and access to medical treatment often functioned as currency in these clientelist interactions, and the Cisterns Program led to a sharp decline in requests for such goods and services by voters, reinforcing the connection between the cisterns and improved health outcomes.

resilience framework by analyzing how the program moderates the adverse impacts of drought shocks. This resilience-focused perspective, largely absent from prior work, provides new insights into how decentralized infrastructure can buffer vulnerable populations against climate variability.

In doing so, the study complements and extends recent evaluations in various ways. Like Silva, 2015, it uses administrative panel data to estimate the program's causal effects, but over a longer period when the program was more mature and widely implemented. Moreover, it focuses on hospitalization, which is a less extreme but more frequent outcome, allowing for a better assessment of disease burden and cost-effectiveness.[7] Additionally, it employs more recent methodological advances to address staggered treatment timing, reducing potential downward bias associated with conventional methods.

Furthermore, it examines whether the positive impacts identified in specific contexts or population groups, as in Bobonis et al. (2022) and Da Mata et al. (2023), are evident at an aggregate level when the program becomes a large-scale intervention. In this sense, it builds on previous studies by evaluating the generalizability, or external validity, of their findings.[8] While an aggregated approach enables the assessment of the program's effectiveness as a public health policy, it may introduce attenuation bias. Thus, although prior studies provide more precise estimates for specific groups, the impacts reported here offer a lower-bound estimate of the program's overall population-level effects, a contribution especially relevant from a public health perspective (e.g., Oldenburg, 2001; Tulchinsky et al., 2023; Saranya and Kathirvel, 2024).[9]

Finally, this study's most significant contribution lies in its engagement with the growing literature on climate change and adaptation. Although the detrimental effects of drought on health are well-known (e.g., Pachauri and Reisinger, 2007), there is limited empirical research quantifying these impacts, particularly within the context of climate change (see Funari et al., 2012; Bratburd and McLellan, 2024, for reviews).[10] Globally, droughts place additional stress on often fragile infrastructure and underdeveloped systems, increasing the risk of disease outbreaks even after the dry spell has ended. Additionally, droughts may alter behavior in ways that increase health risks; for example, substituting flush toilets with unlined pit latrines to conserve water can raise the likelihood of groundwater contamination (McGill et al., 2019). By examining the intersection of drought, waterborne diseases, and a concrete adaptation strategy, this study contributes to the growing body of literature on the public health impacts of climate change (e.g., Deschenes and Greenstone, 2011), providing new evidence on a relatively low-cost, decentralized adaptation intervention that may be suitable for many settings across the developing world.

2.1. Incorporating climate resilience in impact evaluation

Traditional impact evaluations are designed to assess whether policies improve average outcomes under relatively stable conditions. While appropriate for many development questions, this framework is increasingly misaligned with the realities of climate change. As climate shocks become more frequent and severe, policies that raise welfare in normal periods may still leave populations highly exposed to adverse events (e.g., Tanner et al., 2015, 2017). In this context, improvements in mean outcomes alone are no longer sufficient to characterize sustainable development.

This recognition has prompted growing attention to adaptation and resilience as central objectives of development policy (e.g., Béné et al., 2014; Brooks et al., 2019; Hallegatte et al., 2020). Resilience is commonly defined as the capacity of individuals, households, or systems to absorb, adapt to, and recover from shocks, rather than their level of well-being at a point in time (e.g., Baede et al., 2007; IPCC, 2012; Béné et al., 2015; IPCC, 2022; Barrett and Constas, 2014). Importantly, development gains do not automatically translate into resilience. Interventions that improve health, income, or consumption may fail to reduce sensitivity to shocks and, in some cases, may even increase vulnerability. This distinction between welfare improvement and resilience-building is therefore substantive rather than semantic. Indeed, a growing literature documents instances in which adaptation interventions fail to protect populations under stress or inadvertently worsen outcomes, giving rise to maladaptation (e.g., Eriksen et al., 2021; Chaigneau et al., 2022). These concerns stress the need to evaluate development policies not only by their average effects, but also by how they perform under adverse climatic conditions.

Recent conceptual work has proposed frameworks to incorporate resilience into policy evaluation (see Douxchamps et al., 2017, for review). Much of this literature emphasizes latent capacities – such as social capital, risk management practices, or adaptive potential – and relies on composite indices to capture resilience (e.g., Carlson et al., 2012; Béné et al., 2015; Constas et al., 2022). While

[7] Compared to child mortality, granular hospitalization data offer a more frequent, measurable, and economically grounded outcome for cost-benefit analysis, allowing for more precise estimation of the program's welfare impacts. This is especially true in the Brazilian context, where the cost of hospitalizations is standardized and publicly reported by the national health care system (SUS), facilitating consistent valuation of avoided cases.

[8] This is especially important in the case of Bobonis et al. (2022). It has been noted that experimental research is often assumed to be generalizable; however, generalizability is not an automatic consequence of randomization (e.g., Deaton, 2010; Davis et al., 2017; Banerjee et al., 2017). Hence, in some cases, observational studies can help assess whether the effects observed in specific contexts persist as interventions scale up (see Degtiar and Rose, 2023, for a review).

[9] The contrast with Bobonis et al. (2022) goes beyond the level of analysis. The authors do not assess health outcomes directly but instead rely on well-being indices comprising indicators of food insecurity, depression, and self-reported health status. In contrast, I focus on a directly observed health outcome, providing a more precise measure of health impacts. Moreover, while the authors incorporate rainfall shocks as an additional source of exogenous variation in vulnerability, here, multiple definitions of shocks play a central role in the analysis of resilience.

[10] Most empirical research on this topic consists of case studies, which offer limited capacity for causal inference or for a comprehensive assessment of drought impacts (see Levy et al., 2016, for a review).

informative, such approaches often require detailed household-level data and strong aggregation assumptions, limiting their applicability in many climate-vulnerable settings. An alternative strategy focuses on how policies alter the sensitivity of key welfare outcomes to climatic shocks. Building on economic models that treat welfare as a function of stochastic stressors, this approach measures adaptation by estimating whether interventions reduce the elasticity of outcomes, such as crop yields, income, or health indicators, with respect to climatic variation (e.g., Carleton and Hsiang, 2016; Barreca et al., 2016; Burke et al., 2024b). In this framework, resilience is revealed by changes in the relationship between shocks and outcomes, rather than by improvements in average levels alone (e.g., Barrett and Constas, 2014; Cissé and Barrett, 2018).

Formally, an intervention builds resilience if it weakens the statistical link between climatic shocks and adverse outcomes, that is, if it flattens the welfare-shock gradient (Cissé and Barrett, 2018; Barrett and Constas, 2014; Barrett et al., 2020). In applied settings, this implies assessing whether policies disrupt well-documented relationships between climate variability and human welfare, such as the effects of drought on health (Carleton and Hsiang, 2016).

Despite increasing conceptual emphasis on resilience, empirical studies that jointly evaluate development impacts and resilience remain relatively scarce (Eriksen et al., 2021; Berrang-Ford et al., 2021).[11] This study contributes new empirical evidence to this emerging literature by evaluating the potential of rainwater harvesting (RWH) as a climate adaptation strategy. While the adverse health impacts of drought are well documented (see Levy et al., 2016, for a review), rigorous evaluations of whether real-world adaptation policies successfully mitigate these effects remain limited (Deschenes, 2014; Eriksen et al., 2021; Berrang-Ford et al., 2021). By adopting a sensitivity-based approach and testing whether weakens the impact of drought on waterborne illness, this study offers an explicit and policy-relevant measure of built climate resilience. In doing so, it helps translate resilience from a conceptual objective into a testable empirical question – one that can inform adaptation investments toward strategies that deliver measurable reductions in climate-related risks.

3. Background

3.1. *The Brazilian Semiarid Region*

The Brazilian Semiarid Region (BSR) is one of the largest semiarid regions in the world and the most populous. Covering approximately 1.34 million km,[2] it accounts for 15% of Brazil's territory and is home to more than 31 million people, or 15.3% of the country's population (Fig. 1).[12]

Rainfall in this region is scarce and irregular, typically reaching around 800 mm annually and concentrated over three to four months. Additionally, climatic factors contribute to high potential evapotranspiration levels. As a result, the average rainfall often falls short of the potential evapotranspiration, leading to insufficient water volumes in reservoirs to meet the population's needs (SUDENE, 2021; da Silva et al., 2010).[13]

Rainfall scarcity and variability contribute to recurring droughts with a profound impact on the region. The specialized literature lists numerous health risks associated with drought exposure in such environments (for reviews, see Stanke et al., 2013; Brown et al., 2014). For instance, reduced precipitation and increased evapotranspiration can lead to declines in groundwater and surface water levels, which concentrate pathogens in remaining water and elevate the risk of waterborne diseases (Semenza and Ko, 2023). Additionally, the stress caused by water scarcity can lead to mental health issues that are usually absent in drought-free communities (Coelho et al., 2004).[14]

In conjunction with climatic challenges, the Semiarid region is the least developed area in the country, with socioeconomic indicators consistently falling below the national average. For example, the average per capita income in the region is approximately 42% of the national average, and 58% of households live below the poverty line. Other social indicators, such as illiteracy, child mortality, food insecurity, and inequality, are also concerning in this region (IBGE, 2011; Silva, 2021).

3.2. *The semiarid as a policy region*

The Semiarid is more than just a geographic concept; since 1989, its delineation has been central to development policies implemented by the federal government in collaboration with state and local authorities. These policies aim to address issues such as poverty and illiteracy, promote economic growth, and reduce regional inequalities.

[11] Empirical studies often examine how specific interventions affect outcomes during extreme climate events, or use the stochastic nature of such events as an identification strategy (see Dell et al., 2014; for a review), without explicitly framing these effects in terms of adaptation or resilience. Recent contributions, however, increasingly adopt a resilience-focused perspective (e.g., Lane, 2024).

[12] If considered an independent nation, it would rank as the 20th largest country by area and be among the 50 most populous countries in the world.

[13] In addition to low precipitation, 70% of the region is situated on a crystalline geological basement, with shallow bedrock, which restricts the recharge capacity of underground aquifers (SUDENE, 2021). Consequently, over 90% of rainfall is lost through evaporation or surface runoff (da Silva et al., 2010).

[14] Droughts also threaten agricultural activities in a region where many households depend on subsistence farming (Mendes, 1997). The predominantly sandy or sandy-clayey soils have low agricultural potential and limited water retention capacity. Additionally, 82% of the region's soils suffer from low fertility due to constraints related to soil depth, drainage, and high exchangeable sodium content.

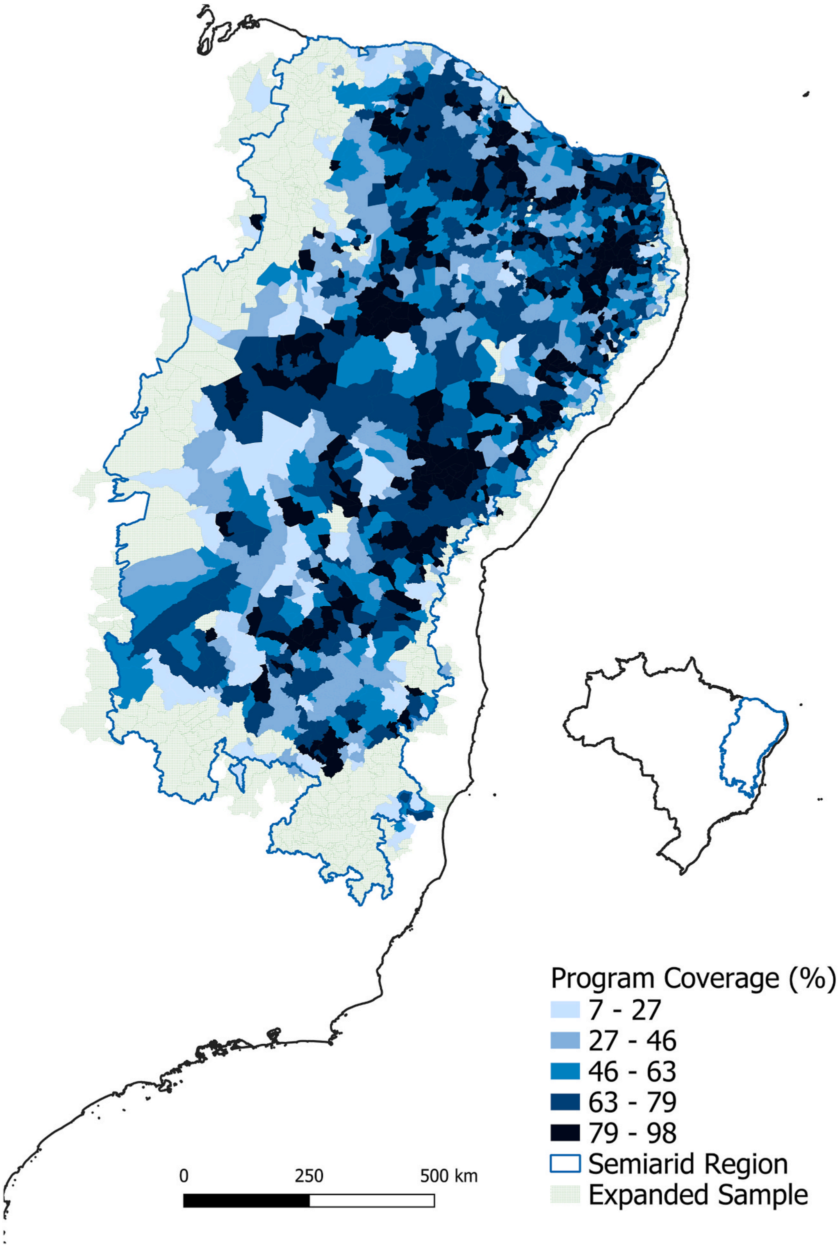

Fig. 1. Brazilian Semiarid Region and Study Sample. Note: The figure shows the official boundaries of the Brazilian Semiarid Region — a policy area delineated by climatic criteria — and the municipalities included in the study sample. Graduated blue shading indicates 2020 program coverage, measured as the share of cisterns constructed relative to demand identified by the Ministry of Social Development. Municipalities shown in dotted green had identified demand but received no treatment by 2020; these serve as the never-treated units in the analysis.

Policies addressing the climatic and economic challenges of the region date back to 1930, with the 1934 Constitution mandating federal intervention in the "Polygon of the Droughts" to mitigate the social and economic impacts of periodic droughts, including famine and large-scale migration to southern cities. However, these policies lacked consistent criteria for defining affected municipalities and were often undermined by clientelism and corruption (Campos and Studart, 2001; Lemos, 2007). By the late 1980s, the Semiarid region was officially recognized as a priority for public development policies, making clearer delimitation necessary. Initially defined in 1995 based on an annual precipitation threshold of 800 mm or less, the classification was refined in 2005 and 2017 using additional technical criteria established by a multidisciplinary committee composed of bureaucrats from various federal agencies. These efforts aimed to ensure a more objective and transparent approach to policy targeting and resource allocation. The following parameters have been in effect since 2005:

A. Average annual precipitation of 800 mm or less,
B. Thornthwaite Aridity Index of 0.5 or less, and
C. Daily percentage of water deficit of 60% or more across all days of the year (a proxy for measuring drought risk).[15]

Climate change is reshaping the BSR ecosystem. Municipalities outside the official BSR boundaries but located near its borders are becoming drier and more similar to the semiarid environment. As a result, the region's official delimitation requires periodic reassessment to ensure that its boundaries accurately reflect these evolving climatic conditions.[16] For that reason, the 2005 Technical Report recommends that the delimitation of the Semiarid Region be reviewed every decade to keep pace with the rapid changes in climate. In 2005, the official delimitation of the BSR included 1135 municipalities. Subsequent revisions added 342 municipalities and excluded 50 that did not meet the criteria when reassessed using more precise data. Consequently, the current official delimitation of the BSR includes 1427 municipalities (IBGE, 2021).[17]

3.3. The Cisterns Program

Over the years, the Brazilian government has implemented various policies to address water insecurity and climate stress in the BSR. Historically, federal and regional agencies implemented top-down interventions centered on large-scale infrastructure projects like dams and reservoirs. However, these initiatives have often been marked by corruption scandals and questionable distributional effects, contributing to the so-called “drought industry”, i.e., a cycle of palliative measures targeted at large private properties that ultimately concentrated land and water resources among a few landowners, deepening existing social tensions and inequalities (e.g., Aguiar et al., 2019; Goncalves, 2018; Soares, 2013; Villa, 2001; Rebouças, 1997).

The Cisterns Program marks a significant departure from these traditional top-down approaches. It emerged as a policy proposal during a side event at the Third Conference of the Parties (COP3) to the United Nations Convention to Combat Desertification (1999), held in Recife, Brazil. At this event, various civil society organizations came together to form the Articulation of the Semiarid (*Articulação do Semiárido* - ASA), a coalition of grassroots organizations, including NGOs, unions, cooperatives, associations, and churches.[18]ASA proposed the creation of the Cisterns Program, drawing from earlier pilots conducted by local organizations with financial backing from international NGOs in the mid-1990s. In the late 1990s, additional pilots were carried out with support from the Ministry of the Environment. However, financial constraints prevented the expansion of these initiatives into an actual policy. It was not until 2003 that the program gained priority status and was incorporated into the federal government's Zero Hunger Initiative, becoming the *National Program for Rainwater Harvesting and Other Social Technologies (Cisterns Program)*.[19]

The Cisterns Program builds tanks next to houses to store rainwater collected through gutters and pipes installed on the roof. Fig. A1 shows a typical cistern constructed by the program. Each tank stores 16,000 L of water, sufficient to meet the drinking and cooking needs of a five-member household during an eight-month dry season. The tanks are built with precast concrete plates, a simple and low-cost technology suitable for dry conditions and easily scalable.

Conceived by civil society, the program was designed to be implemented in a decentralized manner under the paradigm of “living with the Semiarid.” This approach recognizes that drought cannot be eliminated but must instead be managed by adapting to the region's climatic conditions and drawing on local knowledge. The Cisterns Program brought this perspective into the public agenda, promoting solutions aligned with the region's socioeconomic and environmental realities and contrasting with the palliative drought-fighting solutions previously adopted (Rahal and Santana, 2020; Castro, 2021). Its bottom-up design is grounded in the concept of *social technology*, emphasizing direct interaction with beneficiary communities (Andrade et al., 2012). The implementation process includes the following stages or dimensions:

[15] Additionally, if a municipality does not meet any of the criteria but is surrounded by municipalities that do, it may also be included based on contiguity. Currently, this applies to for five municipalities. The 2017 Report explores additional criteria, but the limited availability of historical data across the region constrained the classification to these three indicators.

[16] The Brazilian Semiarid, like other semiarid regions around the world, is becoming larger and drier. Some of its driest areas already experience dry spells lasting up to 10 months. Between 1990 and 2022, a total area of 725,000 km^2 transitioned from semi-humid/dry to semiarid. This means that 55% of the transition zone (i.e., sub-humid and humid areas) became semiarid and now experiences dry spells lasting five to six months (Barbosa, 2024).

[17] Only a fraction of this expansion is due to the creation of new municipalities; most of the growth reflects the enlargement of the semiarid ecosystem. If current climate trends persist (IPCC, 2012), future revisions are likely to expand the Semiarid policy area to include more municipalities.

[18] ASA is now a civil society network with nearly 3000 organizations and, besides being the program's original formulator, ASA organizations also became its main implementers on the ground (Castro, 2021).

[19] The “Cisterns Program” is also referred to as “Water for Consumption”, “One Million Cisterns Program”, or “First Water Program.” The latter reflects that the program not only focuses on RWH for human consumption but also encompasses systems for small-scale agriculture (“Second Water”) and rural schools (Castro, 2021). This article focuses exclusively on the program's main components, the “First Water Program.”

A. Social mobilization: Local NGOs, in collaboration with community members, identify and engage potential beneficiaries in accordance with the program's prioritization rules.
B. Capacity building: Beneficiaries and local actors participate in training on cistern construction, maintenance, and safe water management. These activities transfer technical knowledge to communities and strengthen the program's scalability and sustainability.[20]
C. Implementation: Cisterns are constructed through a cooperative process involving trained builders and beneficiary families. This approach aims to foster a sense of ownership, support replication, and prioritize local labor to reduce costs and stimulate the local economy.

The program is implemented by Brazil's Ministry of Social Development (MDS) in partnership with state and local governments and civil society organizations, typically affiliated with the ASA network. These partners are responsible for selecting households according to criteria set by the federal government. To be eligible, households must be located in rural areas, lack access to improved water sources, and be registered in the national registry of low-income households (*Cadastro Único para Programas Sociais – CadÚnico*).[21] The program's operational documents do not list the prevalence of waterborne diseases as a targeting criterion but often refer to the program as a remedy for such illnesses.[22] Since its creation, the program has prioritized the Semiarid Region, although pilot projects have been implemented in other areas of the country (Brasil, 2018). Once a municipality is selected to participate, cistern construction is carried out gradually, since the pace of construction is contingent upon the program's budget (Brasil, 2018; Da Mata et al., 2023).

The Cisterns Program has undergone gradual yet significant expansion and is now present in over a thousand municipalities. Since 2003, it has delivered more than one million cisterns, meeting its original target (that inspired its initial name) in 2014.[23]

A conservative estimate from 2017 indicates that approximately 18% of the Semiarid's population relies on cisterns as one of their primary sources of water (de Lira Azevedo et al., 2017). As expected, the program's presence is more pronounced in rural areas: the 2017 Agricultural Census reports that out of 1.8 million rural properties in the region, 0.99 million have at least one cistern as a relevant water source. By 2020, between 25% and 28% of households in the region had received a domestic cistern, a figure approximately 10% higher than official statistics (Arsky, 2020). This discrepancy may be due to replication by local groups. As mentioned above, the program's third stage encourages the transfer of knowledge to beneficiaries and local organizations, which could lead to spillovers within the same area.[24] Yet, 30% of the region's rural households, or 450,000 rural families, still lack reliable water sources (IBGE, 2019).

One of the program's main practical benefits is bringing water to a significant portion of the population that would otherwise lack access to any safe water source. Indeed, for many rural dwellers in the region, the cistern is an alternative to improvised wells (see Fig. A2), which usually contain higher concentration of contaminants and tend to dry out during the most severe dry seasons (Castro, 2021). Moreover, before the cisterns, alternative water sources were often located far from the households, requiring considerable physical effort to bring water home (e.g., carrying heavy weights for long periods in the sun). Silva (2009) indicates that, in a sample of 1328 beneficiaries, almost 60% of respondents collected water daily and spent a median of 2 h on this task. With the cisterns, households can avoid these taxing physical tasks that usually fall upon women and children.

Furthermore, the installation of cisterns can enhance the effectiveness of other palliative public programs, such as the Water Tanker Policy (*Operação Carro Pipa*). This policy involves delivering small quantities of water to households during extended droughts (Cerqueira et al., 2017). According to ASA representatives, prior to the widespread adoption of cisterns, tankers would visit homes individually, filling small domestic tanks or even buckets with water that would only last a few days and necessitate frequent visits and requests to local authorities. With cisterns in place, communities store larger volumes of water, which benefit not only individual households but also multiple families over an extended period.[25] This reduces the number of trips and streamlines the delivery process.

[20] The educational process emphasizes good sanitation practices. Households receive training in water disinfection and are instructed on essential maintenance tasks such as disconnecting gutters during dry spells, using a designated bucket for cistern water, coating the tank's exterior with lime, and performing an annual bleach cleaning of the tank after the first rainfall. These practices aim to prevent contamination commonly associated with makeshift water sources like ponds, reservoirs, and untreated storage systems (Alves et al., 2014; de Oliveira Moura et al., 2019; Da Mata et al., 2023).

[21] When too many households in the municipality meet these basic criteria, priority is given to those facing food insecurity, extreme poverty, female-headed households, families with young children, families with school-aged children, families with members with special needs, and elderly-headed households (Brasil, 2010b).

[22] All technical studies commissioned by the Ministry (and other entities) mention the program's anticipated effects on waterborne diseases, highlighting the expectation that cisterns should contribute to reducing their prevalence (e.g., Brito et al., 2005; Brito et al., 2005; Brito et al., 2007; Filho and Pazello, 2008; Brasil, 2010b; Funder, 2010). This expectation is further supported by interviews with the program's senior managers.

[23] Fig. A3 shows the cumulative number of cisterns (Graph A) and annual construction (Graph B), with a marked surge in installations between 2010 and 2017. Since then, the program's expansion has stalled.

[24] The spillovers mentioned here operate at the household or community level within the same municipality, for example through reduced disease transmission from treated to nearby untreated households. These mechanisms are central to understanding program effectiveness at lower levels of coverage but do not bias the municipality-level estimates used in this study. By contrast, spatial spillovers across municipalities are conceptually possible but are unlikely to be quantitatively important in this context; explicit tests using neighboring untreated municipalities provide no evidence that such spillovers affect the main results (see Table A16 in the Appendix).

[25] When cistern owners receive water from a tanker, they are required to assist their neighbors, thereby temporarily converting their individual cisterns into a shared community resource.

Additionally, cisterns shift control over water resources from tanker operators to the community, potentially reducing the risk of capture by limiting opportunities for targeted distribution (Bobonis et al., 2022).

Finally, like any public program, the Cisterns Program faces a risk of capture, but evidence shows it has largely avoided this and effectively reached its target population. It has been scrutinized on many occasions, including audits by the National Court of Accounts (TCU) (Castro, 2021) and ongoing monitoring by the National Council for Food Security (Consea), which is composed largely of civil society representatives.[26] The findings of these bodies indicate that there have been no significant implementation problems with the program, and there is confidence that the resources have reached the intended beneficiaries.[27]

4. Methods and data

4.1. Empirical strategies

This study pursues two complementary objectives. First, it conducts an impact evaluation to assess the welfare gains generated by the Cisterns Program, focusing on health outcomes. Second, it evaluates whether the program enhances the capacity of local populations to withstand extreme weather events, specifically, droughts. Each objective is addressed through specific empirical strategies.

4.1.1. The impact evaluation

The first hypothesis posits that access to decentralized water infrastructure through the Cisterns Program improves household well-being in climate-vulnerable regions by reducing the incidence of waterborne diseases. To test this, I exploit the program's gradual implementation and employ a staggered difference-in-differences (DID) framework that accounts for variation in treatment timing and treatment effect heterogeneity across cohorts.[28] The main specification employs the estimator proposed by Callaway and Sant'Anna (2021), hereafter CSDID. The approach identifies cohort–time-specific average treatment effects, $ATT(g,t)$, by implementing a sequence of two-by-two DID comparisons between municipalities first treated in period g and an appropriate control group consisting of either *never-treated* municipalities or municipalities not yet treated in period t.

To illustrate the intuition, consider a simple two-period comparison involving the last pre-treatment period ($g - 1$) and a later period t. Let $Disease_{mt}$ denote the hospitalization rate due to waterborne diseases (cases per 100,000 residents) in municipality m at time t. For municipalities first treated in year g, the treatment effect at time t can be obtained from the following regression:

$$Disease_{mt} = \alpha_1^{gt} + \alpha_2^{gt} \cdot \mathbb{I}\{G_m = g\} + \alpha_3^{gt} \cdot \mathbb{I}\{T = t\} + \beta^{gt} \cdot (\mathbb{I}\{G_m = G\} \times \mathbb{I}\{T = t\}) + \varepsilon^{gt}$$

where $I\{G_m = g\}$ is an indicator for municipalities belonging to the cohort first treated in year g, and $I\{T = t\}$ indicates observations in period t. In this setup, the coefficient β^{gt} captures the $ATT(g,t)$. Under the assumptions of no anticipation and parallel trends, this parameter admits a causal interpretation.

Because the number of cohort–time-specific effects is large and difficult to interpret individually, I report aggregated treatment effect parameters. First, to facilitate interpretation and provide a summary measure comparable to conventional DID estimates, I compute an overall average treatment effect that aggregates $ATT(g,t)$ across all treated cohorts and post-treatment periods:

$$ATT^{all} = \sum_{g \in G} \sum_{t \geq g} w_{gt} ATT(g,t) \tag{1}$$

Where the weights, w_{gt}, depend on the relative size of cohort g among all groups that ever participate in the treatment, and the number of post-treatment time periods for a particular group.

Second, to trace out the dynamic evolution of hospitalization rates before and after program – and to provide a partial assessment of pre-treatment trends – I aggregate the $ATT(g,t)$ into event-time (dynamic) treatment effects. Let $e = t - g$ denote the number of periods since adoption. The event-time effect at exposure length e is given by:

[26] Between 2003 and 2018, the Council deliberated multiple times on various administrative acts related to the program, including its budget allocations. Examples of such deliberations include Resolutions No. 007/2004, 008/2004 and 001/2005. These and other statements by the Council regarding the Cisterns Program are available at https://www.gov.br/secretariageral/pt-br/consea/acervo-consea/notas-tecnicas (last visited on August 20, 2024).

[27] These audits are corroborated by various tests reported in the Appendix, which indicate that municipalities in the Semiarid with lower precipitation and worse socioeconomic development indicators have higher program coverage (see Section A4).

[28] This empirical strategy follows recent advances that address limitations faced by two-way fixed effects (TWFE) in setting with multiple treatment periods (e.g., Goodman-Bacon, 2021; Callaway and Sant'Anna, 2021; de Chaisemartin and D'Haultfœuille, 2020; Baker et al., 2022). Observational studies have traditionally relied on the canonical TWFE model to estimate policy effects, typically using specifications of the following general form: $Disease_{mt} = \delta Cisterns_{mt} + \beta_k X_{mt} + \alpha_m + \gamma_t + \epsilon_{mt}$ Where $Disease_{m,}$ represent the hospitalization rate due to waterborne diseases in municipality m at time t. $Cisterns$ is an indicator for the post treatment period. X is a vector of controls. α and γ are municipality and year fixed effects, respectively. The results from these conventional estimations indicate a substantial reduction in disease burden following the program's introduction, consistent with the main estimates (see Section A8 of the Appendix). However, the Goodman-Bacon (2021) and de Chaisemartin and D'Haultfœuille (2020) decompositions of the TWFE model indicate that these results, though sizable and statistically significant, may be biased downward due to "forbidden comparisons" and the presence of negative weights (see Table A5).

$$ATT^{es} = \sum_{g \in G} w_{ge} ATT(g, g+e) \quad (2)$$

Where weights w are proportional to cohort size among units observed e periods from treatment.

In all estimations, standard errors are clustered at the municipality and intermediate region levels.[29]

Selection into Treatment and Program Targeting: A data-driven examination of the program's treatment timing and intensity indicates that its implementation closely follows the eligibility criteria outlined in the program's rules. Section A4 of the Appendix presents the results of a series of regressions that use pre-program data to identify the factors driving selection into treatment and program coverage. This analysis examines the relationship between program timing and coverage and 52 health outcomes and 33 climate and socioeconomic variables, totaling 170 tests.

Most tests return estimates that are not statistically different from zero. The statistically significant tests reveal that prioritization is fundamentally based on water scarcity (e.g., precipitation, duration of dry spells, and the presence of surface water bodies) and social vulnerability (e.g., lower local GDP and higher illiteracy rates). Municipalities with more rainfall and better socioeconomic indicators tend to enter the program later and exhibit lower levels of coverage by the end of the sample period. Municipalities with higher prevalence of waterborne diseases tended to enter the program earlier. However, this association reflects the correlation between disease burden and underlying vulnerability rather than explicit health-based targeting. Once these indicators are accounted for, disease prevalence does not independently predict treatment.[30]

4.1.2. Testing program-built resilience: drought shocks and waterborne disease

The second hypothesis focuses on the program's role in strengthening climate resilience. Specifically, it assesses whether access to rainwater harvesting mitigates the adverse health impacts of drought. To evaluate this, I estimate the causal effect of drought shocks on waterborne disease incidence and test whether program exposure moderates this relationship. The analysis leverages plausibly exogenous variation in rainfall to identify the health impacts of transitory shocks and their interaction with the program. This strategy builds on a growing literature that uses extreme weather events as natural experiments (*cf*., Maccini and Yang, 2009; Rocha and Soares, 2015; Bobonis et al., 2022; Barrero Guevara et al., 2024). It permits a causal interpretation under standard identifying assumptions. To reduce concerns about endogenous treatment assignment, the sample is restricted to municipalities that eventually receive the intervention.[31]

To unpack this hypothesis, I begin by identifying the specific type of climate shock most relevant to the Semiarid Region and its effects on the incidence of waterborne disease. I then examine whether and how the Cisterns Program mitigates these effects, considering both a binary indicator for program participation and continuous measures of program coverage. The specifications underlying each step are described below.

Identifying the Effect of Drought: To determine which type of climate shock is most relevant for waterborne disease incidence in the Semiarid Region, I regress hospitalization rates on measures of drought intensity using specifications commonly employed in the climate–economy literature (see Burke et al., 2024, for review). The baseline specification is:

$$Disease_{m,t} = \alpha + \beta \text{Shock}_{m,t-1} + \gamma_m + \theta_t + \mu_{m,t} \quad (3)$$

Where $Disease_{mt}$ represents the hospitalization rate due to waterborne diseases in municipality m during period t. The variable *Shock* indicates the occurrence of a rainfall shock (i.e., a drought) in the previous period. Section 4.2 discusses and evaluates multiple operational definitions of drought shocks; in the baseline specification, a municipality is defined as experiencing a transitory negative rainfall shock when precipitation in the prior year falls below its historical 20th *percentile*. γ and θ are municipality and time fixed effects, respectively. And, μ is the error term.

To address potential spatial clustering among the variables (and shocks), the main specifications utilize spatially robust Conley standard errors (Conley, 1999), allowing for arbitrary serial correlation throughout the panel (Hsiang, 2010; Colella et al., 2023).[32] In the main specifications, the error term is assumed to be correlated up to a distance of 50 km, which corresponds to more than twice the average distance between neighboring municipalities in the Semiarid Region (approximately 21 km).

How the Cisterns Program Moderates Climate Shocks. The previous exercise maps the relevant types of shocks and validates an operational metric for analyzing a more complex dynamic: whether the Cisterns Program can mitigate the adverse effects of rainfall shocks. In this second exercise, the health outcome becomes a measure of vulnerability to climate shocks. For the Cisterns Program to

[29] *Intermediate Regions* are territorial divisions established by the Brazilian Institute for Geography and Statistics (IBGE) to group municipalities with high economic, social, and territorial integration (IBGE, 2017). By clustering the standard error at this level, the analysis accounts for potential spillover effects across neighboring cities with high levels of interdependence.

[30] Table A1 in the Appendix reports a formal test of program selection, in which treatment timing is regressed on pre-program waterborne disease rates while controlling for socioeconomic and climatic characteristics. Once these controls are included, pre-treatment prevalence of waterborne diseases does not predict treatment timing.

[31] There may still be concerns regarding selection bias in treatment timing. However, as shown in Section A4, the observable factors influencing treatment selection and timing are primarily climate characteristics that are either quasi-fixed or follow long-term trends (e.g., precipitation) and are thus absorbed by the fixed effects. Other potential factors are addressed through additional controls incorporated in the robustness checks.

[32] Additionally, alternative clustering approaches – accounting for error correlation at the levels of "intermediate regions" or climate zones – are included as part of the robustness checks.

work as a climate adaptation strategy, it needs to mitigate or neutralize the adverse effects of climate shocks on health indicators, thereby improving resilience. To examine this dynamic, an interaction term is added to Equation (3), yielding:

$$Disease_{m,t} = \beta_0 + \beta_1 Shock_{m,t-1} + \beta_2 T_{m,t} + \beta_3 Shock_{m,t-1} \cdot T_{m,t} + \alpha_m + \theta_t + \mu_{m,t} \quad (4)$$

Where T_{mt} is a binary indicator equal to one if the municipality m is in the post-treatment period. In this setup, the coefficients of interest are β_1 and β_3. In the absence of the Cisterns Program, β_1 captures the effect of a climate shock. β_3 tests whether the relationship between disease burden and climate shocks changes when the shock occurs in a municipality participating in the Program.

Interaction between Shock and Program Coverage. All previous specifications treat the Cisterns Program as a binary intervention; however, the program was implemented gradually across and within municipalities. This variation in treatment intensity makes it possible to evaluate the level of program coverage required to neutralize the adverse health effects of droughts. To conduct this exercise, Equation (4) is revised to include a continuous treatment variable (C_{mt}) that indicates the percentage of the targeted population covered by the program (with $C \in [0,100]$)), as follows:

$$Disease_{m,t} = \beta_0 + \beta_1 \text{Shock}_{m,t-1} + \beta_2 C_{m,t} + \beta_3 \text{Shock}_{m,t-1} \cdot C_{m,t} + \alpha_m + \theta_t + \mu_{m,t} \quad (5)$$

Treatment of Potential Confounders. To improve the credibility of the empirical design, some specifications incorporate controls to address potential confounders. These covariates account for both structural municipal characteristics and time-varying factors that may influence health outcomes or program implementation. Specifically, I construct six principal components that jointly explain 92% of the variance in the following variables: population, expenditures on education and sanitation, rural population share, enrollment in the national conditional cash transfer program, share of the population with access to improved water and sanitation services, temperature, and surface water area (e.g., rivers, reservoirs, lakes). These controls help mitigate potential bias arising from local determinants of program placement, policy responses to drought, or changes in health and sanitation services. In alternative specifications of Equations (3) and (4), program coverage is also included to account for differences in treatment intensity.

4.2. Data

This study combines data from several administrative databases and surveys produced by various Brazilian institutions.[33]

Dependent Variable: The study's outcome variable is *hospitalization rate due to acute diarrheal infections (ADI)*; it includes all severe cases of intestinal tract infections caused by bacterial, viral, and parasitic organisms that led to hospitalization, even if the stay lasted only one day.[34] The rate is calculated at the municipal level and is expressed as cases per 100,000 residents. For age-specific analysis (children under 4 and adults over 60 years old), the rate is adjusted using the corresponding population group.[35]

Hospitalization data come from administrative records produced by medical facilities and classified according to the International Classification of Diseases (ICD-10). These data include the patient's municipality of residence, the municipality where the hospitalization occurred, and the main diagnosis. The analysis uses the patient's municipality of residence, where exposure to contaminated water is most likely to occur.

Section A6 of the Appendix presents the evolution of hospitalization rates over time and around the treatment date. Fig. A7–A9 report trends for the full set of Brazilian municipalities as well as for the study sample, comparing municipalities inside and outside the Semiarid Region over time and around the treatment period. These graphs show that, over the study period, treated municipalities gradually caught up with the rest of the country, indicating a substantial convergence in health outcomes.

Treatment variable: The main treatment variable is an indicator equal to one in years when a municipality participates in the Cisterns Program and zero otherwise. This variable comes from program data that are publicly available and provided by the Brazilian Ministry of Social Development (MDS), which funds and oversees the program's implementation.

Alternative specifications use a continuous treatment definition based on program coverage. Program demand is calculated by the ministry using microdata from the national registry of low-income households (*Cadastro Único para Programas Sociais, CadÚnico*), which includes information on water access. Program records also provide the geographic location of each cistern and its construction date. Thus, the continuous treatment measure is the proportion of the potentially eligible population covered by the program and conceptually ranges from 0 to 100.

[33] For the full list of data sources, see Section A7 of the Appendix.

[34] These infections are typically spread through contaminated food or water, or via person-to-person transmission due to poor hygiene (Brasil, 2010a, p. 155) and are registered under the following ICD10 codes: A00 Cholera, A01 Typhoid and paratyphoid fevers, A02 Other salmonella infections, A03 Shigellosis, A04 Other bacterial intestinal infections, A05 Other bacterial foodborne intoxications, not elsewhere classified, A06 Amoebiasis, A07 Other protozoal intestinal diseases, A08 Viral and other specified intestinal infections, and A09 Diarrhea and other gastroenteritis and colitis of infectious and unspecified origin.

[35] The specialized literature often adopts broader definitions of waterborne diseases that extend beyond ADI (e.g., Ortiz-Prado et al., 2022). Accordingly, an alternative metric includes diarrheal infections as well as other illnesses directly linked to exposure to or ingestion of contaminated water. The list of diseases included under this definition and the criteria for their selection are reported in Table A2 of the Appendix. This broader definition also includes illnesses more commonly associated with other climate events, such as leptospirosis outbreaks caused by flooding (Brown and Murray, 2013). While cisterns may provide some protection against contamination from household surroundings, the program's primary objective is to help households cope with drought, which the literature generally links to a more specific set of diseases (Sugg et al., 2020). Unless otherwise noted, references to waterborne diseases in the main text correspond to narrower definition presented in this section.

Definition of climate shocks. The analysis of climate resilience interacts the treatment variables with alternative definitions of drought to examine whether the program moderates their effects on health outcomes. One of the key challenges in studying the effects of drought is defining an operational metric for rainfall shocks, that is, determining what constitutes a drought and selecting the appropriate time scale (Salvador et al., 2020). The baseline definition (20th *percentile*) is constructed using station-level precipitation data for the period 1961–2020 (Xavier et al., 2022). This threshold is considered a reasonable benchmark for low rainfall by the American Meteorological Society (see Bergemann et al., 2015) and is widely adopted in empirical research (e.g., Jayachandran, 2006; Sarsons, 2015; Shah and Steinberg, 2017; Kaur, 2019; Dessy et al., 2019).

Fig. 2 illustrates the relationship between precipitation quintiles and waterborne diseases within the sample of municipalities that eventually received treatment. The graphs reveal a clear negative association between precipitation levels and disease burden.[36]

The 20th percentile definition of drought is used as the baseline measure because it represents a rather common shock in the region (see Table A17) and provides a simple and interpretable benchmark. Alternative specifications use other definitions of drought shocks. These include rainfall anomalies exceeding one standard deviation below historical means, as well as severe drought thresholds based on the Standardized Precipitation Index (SPI) (<-1.5), the Standardized Precipitation Evapotranspiration Index (SPEI) (<-1.5), and the Palmer Drought Severity Index (PDSI) (<-3). Additional details are provided in Section A13 of the Appendix.

Covariates and Additional Data Sources. Alternative specifications and robustness tests evaluate the sensitivity of the main results to the inclusion of additional covariates (see Section A7 of the Appendix for data sources and detailed definitions). These variables capture local economic conditions, demographic characteristics, climate conditions, and public expenditures. Specifically, the controls include local GDP and population, the number of families enrolled in the national conditional cash transfer program (Bolsa Família), precipitation and temperature, municipal budget expenditures on education, health, and sanitation, total surface water area within the municipality, the share of the population with access to treated water and sewerage services, and the rural population share.

The analysis of potential moderators (Section 6) uses data from a survey administered to beneficiaries of the Cisterns Program upon completion of each cistern. The survey collects information on the cistern's location, construction date, beneficiaries' socioeconomic status, health conditions, and other relevant characteristics. The dataset covers approximately 95% of all cisterns constructed to date. The data are aggregated at the municipal level and used to identify factors that may strengthen or weaken the program's impacts.

The primary analysis spans 23 years, from 1998 to 2020. However, certain specifications cover a shorter period of 19 years (2002-2020) due to missing data for some covariates.

The final sample consists of 1642 municipalities, of which 1198 were eventually treated during the sample period, while 444 remained untreated. Among these municipalities, 1477 are located within the Semiarid region, including municipalities provisionally excluded in the 2022 revision, and 165 lie outside the region but either border it or are adjacent to a treated municipality. The basic composition of the sample is summarized in Table 1, and the spatial distribution of both treated and untreated municipalities is shown in Fig. 1.[37]

Table 2 reports descriptive statistics for the main variables at three points in time: pre-treatment (2000-2002), mid-period (2010), and post-treatment (2022).

5. Main results

The analysis proceeds in two steps, corresponding to the two main hypotheses. First, I estimate the direct effects of the Cisterns Program on hospitalization rates due to acute diarrheal infections, providing an impact evaluation of access to decentralized rainwater infrastructure. Second, I assess whether the program improves climate resilience by mitigating the health impacts of drought shocks. Each part presents the main results and points to relevant robustness checks.

5.1. *The impacts of the Cisterns Program on waterborne diseases*

Table 3 shows that the Cisterns Program significantly reduces hospitalization rates due to acute diarrheal infections (ADI). The table reports the aggregated *Average Treatment Effect* (ATT) of the Cisterns Program on hospitalization rates (measured as cases per 100,000 residents) across three population samples (the crude rate for the entire population, and age-specific rates for children aged 4 years or younger and adults aged 60 years or older). The aggregated ATT is computed using the aggregation procedure defined in Equation (1); hence, the coefficient for the Cisterns Program is the weighted average of all group-time ATTs with weights proportional to group size. Panel A uses never- and not-yet-treated units as the control group and serves as the baseline estimation. Panel B uses only never-treated municipalities as the control group.[38]

Using Panel A as a reference, the results indicate that the Cisterns Program has significantly improved public health indicators in the region. The program is associated with a reduction of 176 severe cases of ADI among the entire population (column 1), representing

[36] For an examination of these relationships using alternative precipitation and drought measures, see Fig. A19 in the appendix.

[37] The program rollout is available in Appendix (see Fig. A3).

[38] Conceptually, never-treated units are municipalities that did not receive any cisterns during the sample period but could have. Empirically, this control group consists of: (i) municipalities that joined the program after the study period, i.e., post-2020; (ii) municipalities within or adjacent to the Semiarid region that border treated municipalities; and (iii) municipalities within or adjacent to the Semiarid region that received pilot projects but had very low program coverage by 2020 (less than 6.98% of their demand). For a discussion of the objective criteria used to select these municipalities and the consequences for the empirical analysis, see Section A2 of the Appendix.

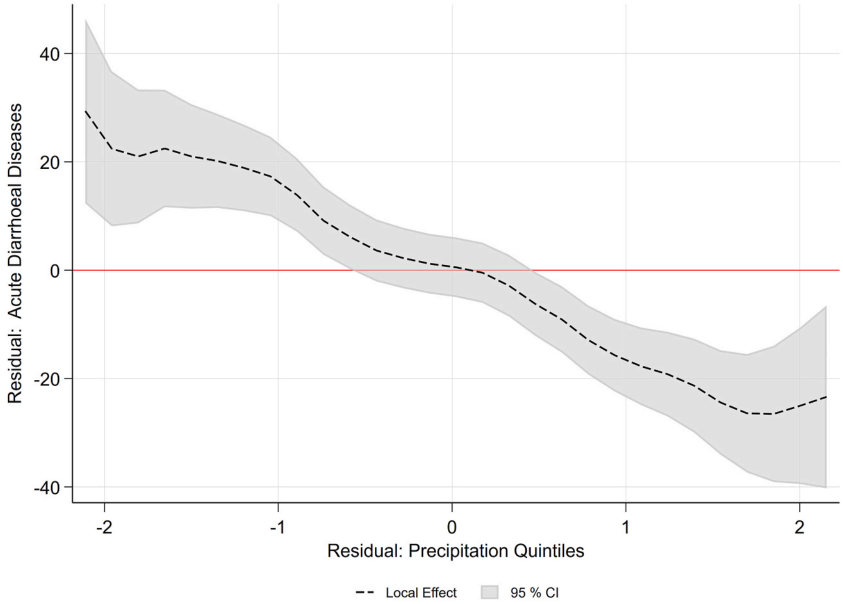

Fig. 2. Local Polynomial Regression: Precipitation Quintiles and Waterborne Diseases. Note: The graphs present local polynomial regressions of the residuals of hospitalization rates (measured in cases per 100,000 residents) on the residuals of the precipitation quintiles. These residuals are derived from regressions that control for year and municipality fixed effects, as well as municipality-specific time trends. To ensure unbiased estimates near the distribution extremes (Li and Racine, 2023), the top and bottom percentiles of the residuals for climate variables are excluded.

Table 1
Sample composition.

	Location		
Treatment Group	Semiarid	Around Semiarid	Total
Eventually-treated	1169	29	1198
Never-treated	308	136	444
Total	1477	165	1642

a sizable 34% decrease relative to the sample average. Moreover, severe ADI cases among children declined by 326, a 22% reduction compared to their sample average (column 2), while cases among adults over 60 dropped by 488, corresponding to a remarkable 47% decline (column 3). These findings underscore the program's effectiveness in mitigating severe health risks, especially for some of the most susceptible segments of the population.

For a causal interpretation, one must assume that treated and control groups would follow similar trajectories in the absence of treatment. To partially validate this parallel trends assumption (PTA), I use a dynamic DID specification to visually assess of treatment effects over time (Marcus and Sant'Anna, 2021). Fig. 3 shows the event-study plot of estimated ATTs, aggregated by the relative time at which municipalities joined the Cisterns Program, as in Equation (2), based on the baseline model (Table 3, Panel A).[39]

The plots show coefficients that fluctuate around zero during the pre-treatment period, with no discernible differential trends between treatment and control groups, providing partial support for the parallel trends assumption. In the post-treatment period, the estimates become increasingly negative and statistically different from zero, particularly in the analyses using the full sample and the 60+ population, before leveling off around year 11, in a pattern that aligns with the program's phased implementation (Fig. 3a and c).

The event-study analysis for children aged 4 years or younger warrants caution. Period-specific ATTs take longer to reach statistical significance and remain only marginally significant after year 10, which suggests that this estimation may not pass more demanding pre-trend tests. Two factors may explain this: first, as children age out of the sample, the treated population changes more rapidly, hindering the accumulation of effects. Second, the use of doubly clustered standard errors may be overly stringent for this subsample.[40] Thus, while any causal interpretation of these estimates must be approached with care, it is possible that the effects persist as these individuals age, influencing other age groups and being captured in the overall population rather than within this specific stratum.

[39] Event-study plots for alternative control groups are in Section A9.2 of the Appendix. Appendix Figure A13 further reports cohort-specific event-study estimates for early- and late-treated municipalities.

[40] In specifications that cluster standard errors only at the panel level (not reported), the estimates for this population group pass all tests performed here.

Table 2
Descriptive statistics.

Variable	2000-2002			2010			2020-2022		
	Treatment	Control	Difference	Treatment	Control	Difference	Treatment	Control	Difference
Hospitalizations: ADI[†]	861.53	630.65	230.80***	620.40	500.91	119.49*	120.51	157.87	−37.36
Hospitalizations: ADI, Children ≤4	2188.59	1895.46	293.13	1938.19	1624.48	313.71*	486.70	583.76	−97.06
Hospitalizations: ADI, Adults 60+	1846.46	1051.34	795.13***	1251.17	878.01	373.15***	163.38	200.56	−37.19
Precipitation (mm)	810.55	1157.22	−346.67***	704.07	1021.60	−317.53***	977.93	1352.91	−374.98***
Maximum Temperature (°C)	33.16	33.05	0.11	33.55	33.67	−0.12	33.40	33.27	0.13
Rainfall Shock: 20th percentile[‡]	0.02	0.01	0.01	0.16	0.21	−0.04	0.02	0.02	0.01
Revenue from Transfers, per capita	539.03	533.58	5.45	1352.52	1366.34	−13.81	5372.48	5579.41	−206.93
Revenue from Local Taxes, per capita	14.24	17.93	−3.69**	46.90	63.00	−16.10**	227.29	255.85	−28.56
Expenditure: Education, per capita	181.35	173.73	7.62	517.50	485.93	31.57***	5.20	25.21	−20.01**
Expenditure: Health and Sanitation, per capita	117.45	118.33	−0.88	328.52	338.29	−9.77	4.37	20.71	−16.34**
Expenditure: Social Assistance, per capita	33.93	30.73	3.20	84.15	87.23	−3.09	0.81	4.21	−3.40*
Area of surface water (km2)	7.40	4.36	3.04	9.12	4.55	4.57	7.22	4.20	3.02
Access to Treated Water (%)	31.80	31.95	−0.15	54.96	52.31	2.65*	77.61	84.15	−6.54***
Access to Adequate Sewage (%)	27.69	28.98	−1.29	73.58	70.71	2.87	26.73	32.59	−5.86
Local Population (1,000)	18.98	27.92	−8.94	20.43	30.44	−10.01	20.93	31.07	−10.14
Rural Population (%)	53.27	45.98	7.28***	46.72	40.44	6.28***	41.72	35.37	6.35***
Local GDP (Million)	46.99	101.97	−54.98*	124.63	279.10	−154.47*	285.33	591.17	−305.84*
Local GDP (1,000), per capita	2.17	2.45	−0.28	5.04	5.97	−0.931**	11.70	14.12	−2.41**
Number of Cistern, accumulated				256.13	1.65	254.48***	774.84	3.40	771.44***
Program Coverage (%)				26.75	0.12	26.63***	61.31	0.27	61.04***
Number of families enrolled in the CCT program				2858.25	3304.99	−446.74	3046.52	3579.80	−533.28
CCT program, Transfers per capita				15.28	13.71	1.57***	34.09	30.97	3.11

Note: The table reports means for the main variables used in the analysis. [†]ADI = Acute diarrheal infections (cases per 100,000 residents). ‡ Proportion of municipalities experiencing a shock. When data for 2000 are not available, values are drawn from the most recent observations in the 2000–2002 window; similarly, 2022 values are based on the latest data from 2020 to 2022, yet fiscal data for 2020–2022 should be interpreted with caution due to incomplete reporting. The treatment group consists of municipalities that eventually participate in the Cisterns Program (N = 1198), while the control group includes neighboring municipalities never treated or treated only after 2020 (N = 444). Differences are based on pairwise t-tests. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 3
The effect of the cisterns program on hospitalization.

Variables	All cases (1)	Children ≤4 (2)	Adults 60+ (3)
Panel A. *Comparison group: never treated and not-yet treated*			
Cisterns Program	−175.6***	−326.2***	−488.6***
	(44.4)	(111.3)	(103.3)
Panel B. *Comparison group: never treated only*			
Cisterns Program	−172.8***	−305.6***	−499.0***
	(46.0)	(115.8)	(110.0)
Observations	37,723	37,608	37,671
D. V. Mean	523.0	1,498.8	1,041.6
Treated	1,198	1,193	1,198
Untreated	444	444	444

Note: The table presents the aggregated *Average Treatment Effect* (ATT) of the Cisterns Program on hospitalization rates (measured as cases per 100,000 residents) across three population strata, using the DID estimator proposed by Callaway and Sant'Anna (2021). The aggregated ATT is computed using the aggregation process defined in Equation (1), making the coefficient for *Cisterns Program* the weighted average of all group-time average treatment effects with weights proportional to group size. *D.V. Mean* is the dependent variable mean for the respective sample. In Panel A, the comparison group consists of municipalities that never participated in the program (never-treated) and those that have not yet participated (not-yet-treated). Panel B restricts the comparison to municipalities that were never treated. Bootstrap standard errors, clustered at the municipality and intermediate region levels, are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Additional Robustness Checks: The findings reported above are robust to a battery of robustness checks reported in the Appendix. First, alternative tests of the parallel trends assumption, following Roth (2022) and Rambachan and Roth (2023), broadly support the main results (see Section A11). Second, the results remain consistent after the inclusion of covariates, incorporated using the doubly-robust approach proposed by Sant'Anna and Zhao (2020) (See Section A9.1).[41] Third, the results are also robust to different formulations of the dependent variable: using a broader measure of waterborne diseases yields statistically significant ATT estimates with slightly larger coefficients (Tables A7 and A8), suggesting that the program also impacts less common diseases transmitted through contaminated water. Furthermore, the results remain robust to normalization of the dependent variable, regardless of covariate inclusion (Tables A09 and A10).

A randomization-based placebo test further evaluates whether the estimated effects could arise spuriously. Specifically, the test assigns placebo treatment timing to never-treated municipalities and re-estimate the main specifications across 1000 iterations. The resulting placebo estimates are centered near zero, with rejection rates close to nominal levels, indicating that the main results are unlikely to be driven by chance (see Table A20).

Finally, Section A10 of the Appendix presents results from a series of falsification tests using hospitalization rates associated with other disease groups, which should not be *directly* affected by droughts or by the program.[42] Table A13 shows that, for these diseases, most estimates are not statistically different from zero. Moreover, none of them yield statistically significant effects across all specifications simultaneously, and when significance arises, the estimates are highly sensitive to the inclusion of covariates (Table A14) and tend to lose significance once other municipality characteristics are accounted for. For the few cases that appear to warrant further examination, event-study plots exhibit patterns inconsistent with the parallel trends assumption (see Fig. A15). This lack of consistency contrasts with the robust and stable results observed for waterborne diseases, further reinforcing the validity of the main findings.[43]

5.2. Assessing built climate resilience

While the previous section documents average health gains from the Cisterns Program, climate adaptation requires assessing how outcomes respond to shocks, with and without the program. A central implication of climate resilience is a reduction in the sensitivity of welfare outcomes to climatic shocks. This section therefore examines whether the Cisterns Program weakens the relationship between drought shocks and waterborne disease incidence. Evidence that droughts increase hospitalizations in untreated municipalities but not in treated ones would indicate that the program reduces vulnerability to climate stress.

Table 4 presents the estimated impacts of drought shocks on morbidity rates associated with acute diarrheal infections (ADI). Column 1 reports results from the basic two-way fixed effects specification. Column 3 incorporates municipality-level controls,[44] while column 5 adds municipality-specific time trends to account for localized changes in policies, disease trajectories, and trends in climate conditions. Lastly, Column 7 reports results from the fully specified model, including fixed effects, controls, and municipality-specific trends. As expected, the results indicate that drought shocks significantly increase hospitalization caused by ADI.[45]

The finding that drought increases the incidence of waterborne diseases is neither surprising nor new. However, this exercise is useful for validating the main operational metric used to evaluate a more complex dynamic: the effectiveness of the Cisterns Program as a climate adaptation strategy. It also helps identify other relevant types of shocks that are less commonly employed in the empirical literature.

As shown in Table 4 (even columns), the coefficient for *Shock* (β_1) is positive and statistically significant across all specifications for hospitalization rates, confirming that severe droughts increase the incidence of waterborne diseases. However, the interaction

[41] The estimates with covariates cover a shorter period, as some covariates are only available from 2002 onward. Stepwise inclusion shows that coefficients remain stable, with changes occurring only after precipitation is introduced. Controlling for precipitation reduces coefficients in Panel A, while those in Panel B remain largely unchanged (see Table A6). Stepwise results are available upon request.

[42] Droughts affect human health through multiple channels, increasing the incidence of waterborne, vector-borne, and respiratory diseases, as well as mental health and nutritional disorders. These effects have been documented across a wide range of disease groups. For example, reduced water availability can increase contamination risks and skin infections, while reliance on stagnant water sources raises exposure to vector-borne diseases. Droughts may also worsen respiratory conditions through reduced air quality and increased particulate matter, and contribute to mental health stress and food insecurity, with downstream effects on nutritional outcomes (for reviews, see Sena et al., 2014; Vins et al., 2015; Levy et al., 2016; Alpino et al., 2016; Sugg et al., 2020; Vos et al., 2021; Mehdipour et al., 2022). Given these diverse health impacts, the tests conducted here are not intended to serve as strict placebo tests. Rather, for diseases plausibly affected by drought through water-related channels, they provide *prima facie* evidence of the program's broader impacts. For diseases with no direct link to water availability or quality, they serve additional falsification tests, helping to rule out the possibility that the results reflect general improvements in health outcomes.

[43] Note that, for the purposes of this falsification exercise, p-values are not adjusted for multiple hypothesis testing precisely to highlight outcomes that may warrant further investigation.

[44] The controls include program coverage (percentage of the eligible population) and six principal components explaining 92% of the variance in local population count, per capita education and sanitation expenditures, rural population share, enrollment in the national conditional cash transfer program, access to water and sewage services, maximum temperature, and area of surface water (e.g., rivers, reservoirs, lakes, etc.). These variables are intended to capture local factors driving the program placement as well as potential policy responses to climate shocks.

[45] Section A13 of the Appendix evaluates alternative drought measures across four specifications of Equation (3). Drought shocks are generally associated with increases in ADI morbidity. While some estimates lose statistical significance when specifications include municipality-specific trends or controls for local characteristics and policy responses, results for the 20th percentile and more severe shock measures remain stable across specifications.

Table 4
Drought shocks and Their Interaction with the Cisterns Program.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Shock	47.4***	128.5***	29.5**	85.9***	28.2***	74.8***	24.5***	86.1***
	(11.8)	(26.2)	(11.8)	(31.8)	(8.9)	(19.8)	(9.0)	(23.9)
Cisterns		32.9		61.0***		24.1		41.3*
		(21.3)		(23.5)		(19.9)		(21.7)
Shock X Cisterns		−113.0***		−71.1**		−64.2***		−78.1***
		(27.9)		(32.7)		(20.5)		(24.5)
Observations	26,337	26,337	22,736	22,736	26,337	26,337	22,736	22,736
Shock with Cisterns ($\beta_1 + \beta_3$)		15.5		14.8		10.6		8.0
		(11.7)		(11.3)		(8.7)		(8.4)
Municipality FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Municipality Trends	N	N	N	N	Y	Y	Y	Y
Controls	N	N	Y	Y	N	N	Y	Y

Note: The table shows the impact of drought shocks on hospitalization rates, expressed as cases per 100,000 residents. Odd-numbered columns report the impact of a shock (Equation 3), while even-numbered columns include the Cisterns Program and its interaction with the shock. All specifications include municipality and year fixed effects (Equation 4). Columns 3 and 4 include controls for local demographic and policy factors that may influence the outcome variables. Columns 5 and 6 include municipality-specific time trends. Columns 7 and 8 include both municipality-specific time trends and controls. Spatially robust Conley standard errors (Conley, 1999) are reported in parentheses, allowing for arbitrary serial correlation (Hsiang, 2010; Colella et al., 2023) and spatial correlation within a 50 km radius of each municipality centroid (the average distance between municipalities is 21 km). ***p < 0.01, **p < 0.05, *p < 0.1.

coefficient (β_3), which captures the differential effect of a shock in municipalities reached by the Cisterns Program, is consistently negative and of similar magnitude to the main shock effect (β_1). Consequently, when a shock occurs in municipalities with the program in place, the combined effect of the shock and the program (i.e., the linear combination $\beta_1 + \beta_3$) is statistically insignificant across all estimations. This finding suggests that the Cisterns Program effectively mitigates, if not fully neutralize, the health impacts of climate shocks.

It is worth noting that for the most reliable estimates – those from models with controls – are substantially smaller, indicating that local characteristics and policies play an important role in buffering the impact of a shock. Furthermore, the similarity of results across specifications with controls and unit-specific trends suggests that these policies and characteristics follow secular trends, with both approaches capturing the same underlying dynamics. Still, even when accounting for these factors, climate shocks continue to have significant adverse impacts on affected municipalities, unless their most vulnerable populations (i.e., low-income households living in rural areas) are protected by the Cisterns Program.

Beyond average treatment effects, it is important to assess whether the protective impact of the Cisterns Program varies with implementation intensity. The program's gradual rollout across and within municipalities generated substantial variation in coverage over time. This variation enables an analysis of treatment heterogeneity by estimating how program coverage influences the relationship between shocks and waterborne disease incidence (Equation 5). In particular, this exercise offers an indication of the coverage level required to buffer the adverse health effects of droughts.

Table 5 reports the estimates from the revised model, confirming the detrimental effects of climate shocks. And once again, across all specifications, these effects are consistently mitigated by coverage of the Cisterns Program. Fig. 4 shows the combined effects of drought shocks on hospitalization rates due to acute diarrheal infections across different levels of program coverage. The estimates suggest that when coverage reaches approximately 50% of the estimated demand, the program fully neutralizes the effect of a shock; that is the point at which the linear combination of β_1 and β_3 becomes statistically insignificant.[46] These findings imply that, to fully offset the type of shock considered here, policymakers should aim for coverage levels of around 50% of estimated demand in each municipality.[47]

Robustness checks: The results remain consistent across a range of additional tests – beyond the inclusion of covariates and municipality-specific time trends – which helps capture common policy responses to crises triggered by severe droughts. First, the findings are robust to alternative definitions of climate shocks. Although more restrictive definitions correspond to rarer events and may yield underpowered specifications, shocks generally increase disease burden across all scenarios (Fig. A18). Importantly, whenever shocks have a significant impact, interaction with the Cisterns Program either fully offsets or substantially mitigates these effects, including under definitions capturing more severe shocks (e.g., sustained low precipitation over 24 months).

The results are also robust to alternative clustering approaches. While the baseline specification employs standard errors that account for spatial correlation and heteroskedasticity, additional tests cluster the errors at the intermediate region level, as municipalities within the same "micro-region" may share common shocks and policy responses due to their proximity (Table A18). Besides,

[46] While this analysis assumes the effects of C are linear, alternative estimations incorporating a quadratic term in Equation (5) yield similar predicted values for the linear combination of variables. The coefficients for the quadratic terms, though positive, are negligible in magnitude and do not significantly alter the overall function shape within the range of C.

[47] More severe shocks may require higher levels of coverage. For instance, when a shock is defined as a year with an average monthly SPEI-12 below −1.5, the level of coverage needed to neutralize its effects on hospitalization rates is closer to 60% (see Fig. A22 in the appendix).

Table 5
Drought shocks and Their Interaction with the Cisterns Program Coverage.

Dependent Variable:	Hospitalization Rate			
Variables	(1)	(2)	(3)	(4)
Shock	82.47***	52.78***	50.13***	49.11***
	(17.58)	(19.33)	(14.02)	(15.48)
Program Coverage (%)	−1.41***	−1.38***	−0.54	−0.69
	(0.45)	(0.48)	(0.47)	(0.49)
Shock x Program Coverage (%)	−1.07***	−0.64	−0.66**	−0.67**
	(0.38)	(0.41)	(0.27)	(0.30)
Observations	26,337	22,736	26,337	22,736
Municipality FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Municipality Trends	N	N	Y	Y
Controls	N	Y	N	Y

Note: The table reports the impact of drought shocks on hospitalization rates (cases per 100,000 residents). All specifications include program coverage, measured as the percentage of the target population, and its interaction with the shock variable. All specifications include municipality and year fixed effects (Equation 5). Column 1 is the baseline estimation with no controls. Column 2 includes controls for local demographic and policy factors. Column 3 adds municipality-specific time trends. Columns 4 includes both controls and unit-specific time trends. Spatially robust Conley standard errors (Conley, 1999) are reported in parentheses, allowing for arbitrary serial correlation (Hsiang, 2010; Colella et al., 2023) and two-dimensional spatial correlation within a 50 km radius of each municipality centroid (the average distance between municipalities is 21 km).***p < 0.01, **p < 0.05, *p < 0.1.

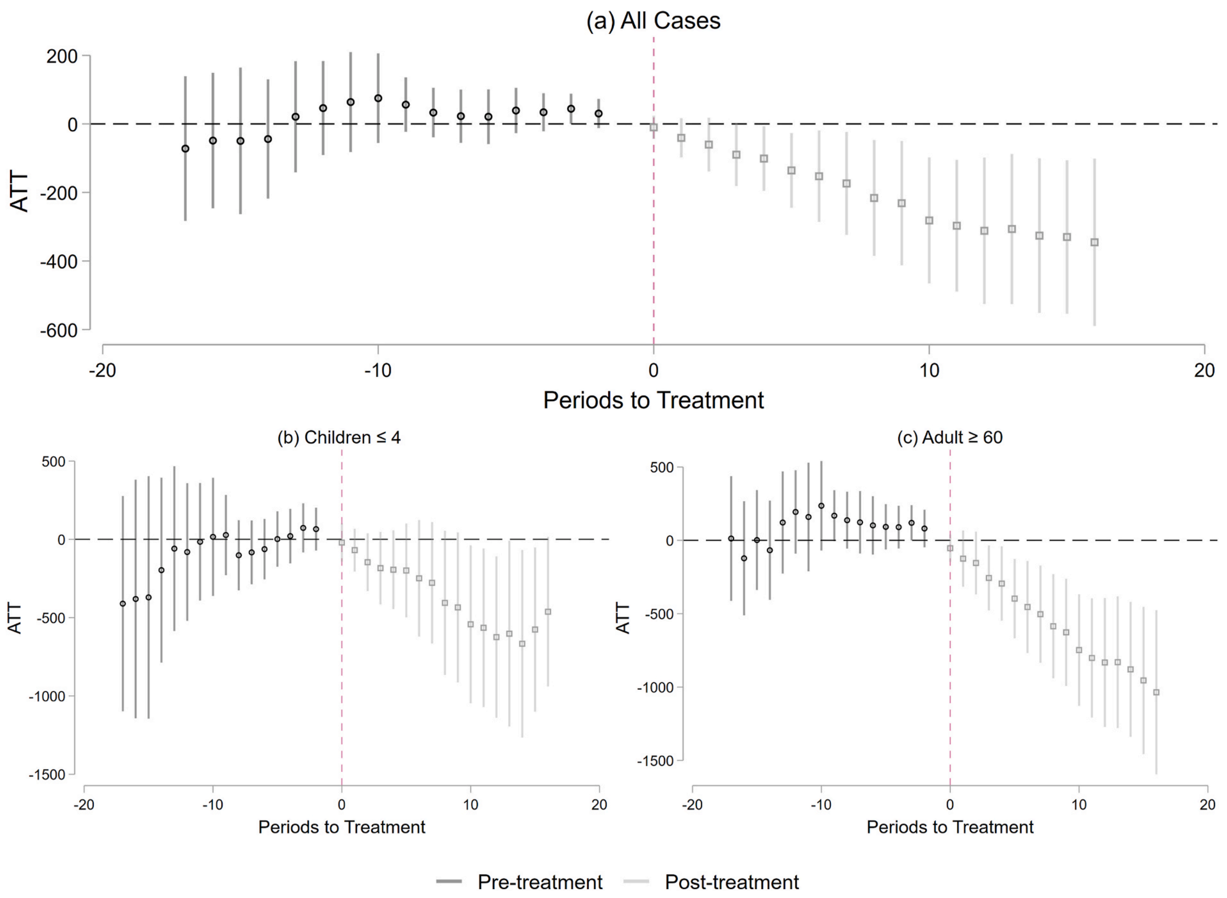

Fig. 3. The Impact of the Cisterns Program on Acute Diarrheal Infections, Note: The figure presents the event study coefficients following the approach of Callaway and Sant'Anna (2021). It displays point estimates along with 95% confidence intervals, indicating the effect of the Cisterns Program on hospitalizations due to acute diarrheal diseases (measured as cases per 100,000 residents) for each period before and after treatment (Equation 2). The comparison group comprises never-treated and not-yet-treated municipalities (as in Panel A of Table 3).

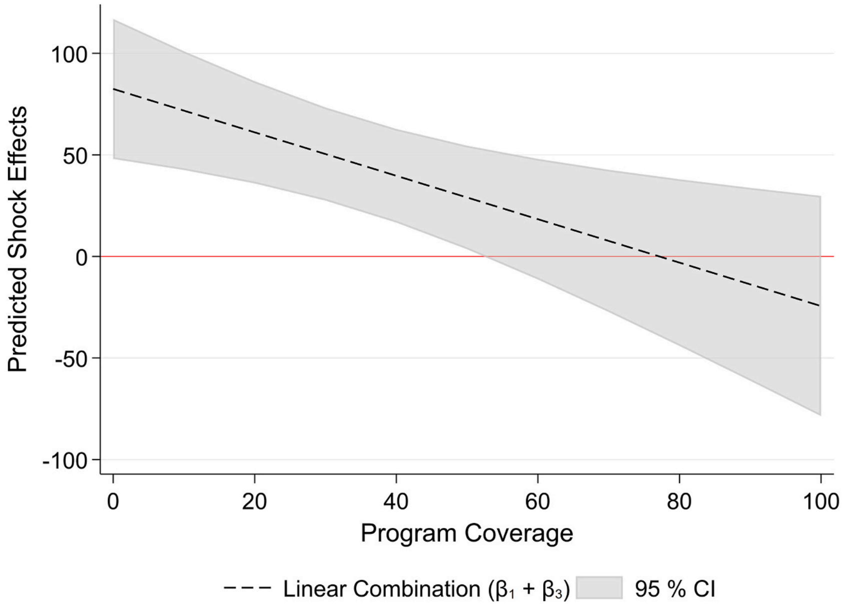

Fig. 4. Drought Shocks and Program Coverage: Combine effects on Waterborne Diseases
Note: The graph shows the predicted effect of a drought shock on hospitalization rates due to acute diarrheal infections (cases per 100,000 residents) at various levels of program coverage. Estimates are based on specifications that include municipality and year fixed effects (Equation 5) and represent the combined effects of *Shock* and program coverage (*C*), i.e., the linear combination of β_1 and β_3. Conley standard errors allow for arbitrary serial correlation and spatial correlation within a 50 km radius of each municipality centroid (the average distance between municipalities is 21 km). Estimations that additionally control for time-varying municipal characteristics and specific time trends are reported in Appendix (Fig. A20).

because climate shocks do not necessarily align with administrative boundaries, alternative specifications instead cluster errors by microclimate zones (Table A19), reflecting the fact that shocks follow climatic and ecological patterns rather than political divisions (e.g., Cooperman, 2017). In all specifications, the standard errors are also clustered at the municipality level to account for autocorrelation in the panel.

To rule out the possibility that the effects of shocks captured here are merely coincidental, I conduct simulations where placebo shocks are randomly assigned to the sample, mimicking the estimations shown in Table 5. In all simulations, artificial shocks always affect approximately 25% of the sample to maintain an occurrence rate similar to that observed in the data. The placebo simulations generate small coefficients and statistically significant estimates at rates close to conventional significance levels (see Table A21 in the Appendix). This provides additional evidence that the main results are not driven by random variation.

Finally, an additional robustness checks examines the relationship between drought shocks and other disease groups, including those not directly related to water quality, with the expectation that the marginal effects of shocks and their interaction with the Cisterns Program are null or substantially smaller than those reported here – subject to the caveat discussed in footnote 50. The results, presented in Figs. A23–25 of the Appendix, show that climate shocks and their interaction with the Cisterns Program have no significant effects for most disease groups, particularly those not identified in the literature as being linked to droughts, such as traffic accidents and sexually transmitted infections.

6. Potential moderators

One could view cisterns as mere water infrastructure serving as insurance mechanisms that smooth water consumption during extended dry spells. While this interpretation is consistent with the performance of municipalities with cisterns during severe droughts, it does not fully capture key aspects of the program and its effects on participating communities. Cistern water is generally of higher quality than alternative unimproved sources (see Figs. A1 and A2), but quality is not guaranteed. Proper management of both the system and the stored water is essential. For example, users must discard the initial runoff to allow the first flush of rainwater to clean the roof, gutters, and pipes, and maintain structures to prevent contamination from animals and disease vectors. In addition, water should be treated before consumption, as untreated cistern water often contains fecal coliforms (Alves et al., 2014; de Oliveira Moura et al., 2019).[48]

It is therefore not surprising that previous studies emphasize the importance of the Program's training component (e.g., Castro, 2021; Pereira, 2016), which not only teaches how to use cisterns but also raises awareness about the risks associated with consuming water from improvised sources (Amorim and Porto, 2001; Brito et al., 2005). Training beneficiaries to manage their water is a central component of the program and was strongly emphasized by its original proponents, particularly organizations withing the ASA network. Consistent with this view, Da Mata et al. (2023) argue that program impacts are driven by improvements in water quality, which are in turn shaped by training and beneficiary education. This section provides additional evidence supporting this argument, stressing the role of education and its connection to water quality as critical drivers of the program effectiveness.

The plausibility of this mechanism rests on the following reasoning. First, individuals with some basic schooling may benefit more from training than those with no formal education. More educated individuals are better able to assimilate information about the (often invisible) risks of contaminated water. They are also more likely to understand the program's guidelines for managing the system and stored water and comply with them. Hence, for these individuals, the program would not only increase water supply during dry seasons but also enhance beneficiaries' control over their water, enabling greater agency over their resources (cf., Sen, 1985;1999) a critical component of water-related improvements in developing settings, according to the WASH literature (e.g., Jalan and Ravallion, 2003; Pickering and Davis, 2012; Barnwal et al., 2017).

Corroborating this reasoning, Table 6 shows that the program has significantly greater impacts in municipalities where the population is relatively more educated. The estimates in the "difference" column (c), which can be interpreted as the coefficient of a triple difference, indicate much larger effects among these communities.[49]

Another piece of evidence from the survey data concerns heterogeneity across implementers. Organizations connected to ASA have been the main partners of the MDS. However, the ministry has also signed agreements with state and local governments to accelerate the implementation of the program. ASA has consistently emphasized the training component of the program, arguing that it is central to making the cistern a *social technology*. If state and local governments place less emphasis on community interaction than social organizations, municipalities disproportionately served by these contracts would be expected to exhibit smaller effects than those predominantly served by ASA-affiliated organizations (cf. Frey, 2022).[50] Table 7 partially corroborates this argument. In municipalities where an ASA organization is the main implementer, the estimated effect is statistically significant and similar in magnitude to the ATT reported in the main analysis. Contrastingly, in municipalities implementation is led by local or state governments, the estimated effect is smaller and not different from zero, rendering the triple-difference estimate statistically insignificant.[51]

Finally, a last piece of evidence builds upon heterogeneity across other dimensions. Table 8 shows that the Cisterns Program tends to have larger effects in places where individuals used to clean their domestic reservoir or treat their water less often. These results provide suggestive evidence that individuals who had more to learn from the program are the ones experiencing the largest effects. At same time, household infrastructure, such as having a septic pit or an in-house restroom, does not explain differences in the program average effects.

This exercise highlights that the program's effects are not merely a result of increased water supply. Instead, the cisterns transfer greater responsibility and control over water resources to beneficiaries, enhancing their agency in water management. Rather than remaining passive recipients of emergency assistance – such as sporadic aid delivered by water trucks (Bobonis et al., 2022) – individuals with higher levels of education are better equipped to understand and utilize this new resource effectively, leading to amplified benefits. Overall, this suggestive evidence underlines the critical role of knowledge and agency as key components of adaptation strategies.

[48] The most common treatments recommended to cistern users include filtration and disinfection, typically through boiling or the use of sodium hypochlorite. Less common methods include flocculation and fluoridation (Brito et al., 2007). While some of these methods may not be feasible for all households in the region, simpler options such as ceramic filters (*velas de Lambreth*) are widespread and generally affordable. These filters remove larger particles and certain bacteria, but their pore sizes (1–20 μm) are too large to block smaller contaminants such as viruses, pesticides, and some chemical compounds (Alves and Assis, 1999). Survey data indicate that 69% of beneficiaries did not use any water treatment method prior to receiving a cistern. However, studies suggest that sodium hypochlorite use increases substantially after program participation; for example, Almeida and Falcao (2020) report that 76% of beneficiaries adopt it, sometimes in combination with filtration. These patterns suggest that the program's training component is a key mechanism for improving water quality.

[49] The Ministry of Social Development (MDS) requires implementers to administer a survey with beneficiaries, collecting information about the head of household, their families and surrounding conditions. This includes information on education, current water sources, and water management practices. The data used in this analysis cover nearly 95% of the cisterns delivered to date. I use these microdata to classify municipalities in the sample according to their average beneficiary characteristics and explore the heterogeneity in treatment effects on waterborne diseases across these subsamples.

[50] State and local governments are not obligated to sign agreements with ASA organizations, though they often do. Hence, the assumption here is that, even when they subcontract some ASA organization, local and state government may impose their own implementation dynamics.

[51] These differences may arise from fundamental disparities between beneficiary groups in each municipality group. Table A23 tests this hypothesis, showing that while municipalities are similar along most dimensions, those with stronger NGO presence tend to receive less public investment in sanitation and health and exhibit lower socioeconomic status, especially in self-reported indicators.

Table 6
Heterogeneity in treatment effects - Education Attainment.

Classification Parameter	More Schooling			Less Schooling			Difference (a-b)
	ATT (a)	Mean	N	ATT (b)	Mean	N	
Illiteracy rate among women 25 or older	−346.6***	893.9	6,003	−140.2***	686.6	31,763	−206.4***
Illiteracy rate 25 or older	−272.2***	723.1	5,773	−144.4***	714.9	31,993	−127.8*
Illiteracy rate (%) - Survey	−239.3***	785.2	14,099	34.6	650.9	12,903	−273.9***

Note: The table reports the Average Treatment Effect on the Treated (ATT) of the Cisterns Program on hospitalization rates due to acute diarrheal infections (ADI) for two groups of municipalities: those with above-average (a) and below-average (b) education levels within the sample. ATT is estimated using the method proposed by Callaway and Sant'Anna (2021), with never-treated and not-yet-treated municipalities serving as the control group. The classification variable used to categorize municipalities is derived either from the 2010 Census (which considers the entire local population) or from the MDS survey (focusing on program beneficiaries only). "Mean" denotes the average ADI hospitalization rate in the period *t-1*, while *N* is the total number of observations included in the estimation. Estimates based on alternative classification variables are reported in Section A16 of the Appendix. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 7
Heterogeneity in treatment effects - Main Implementer.

NGOs			Local or State Govts			Difference (a-b)
ATT (a)	Mean	N	ATT (b)	Mean	N	
−166.5***	740,4	15,410	−78.8	695,2	11.592	−87.7

Note: The table presents the Average Treatment Effect on the Treated (ATT) of the Cisterns Program on hospitalization rates due to acute diarrheal infections (ADI) for subsample classified according to the main local implementers, comparing municipalities where the main implementer is an organization linked to the ASA network to municipalities where the main implementer is the state or local government. ATT is estimated using the method proposed by (Callaway and Sant'Anna, 2021), with not-yet-treated municipalities serving as the control group. "Mean" represents the average hospitalization rate in the period *t-1*, while *N* denotes the total number of observations included in the estimation. ***p < 0.01, **p < 0.05, *p < 0.1.

Table 8
Heterogeneity in treatment effects - Household Habits and Infrastructure.

Classification Parameter	Above Average			Below Average			Difference (a-b)
	ATT (a)	Mean	N	ATT (b)	Mean	N	
Regular Cleaning of Domestic Reservoirs (%)	−87.6*	725.7	14,398	−168.2**	715.6	12,604	80.5
Water treatment (%)	−76.0*	676.0	15,962	−263.8***	785.9	11,040	187.8**
In-home toilet (%)	−180.2***	636.2	14,398	−180.3**	817.7	12,604	0.1
Sanitary pit (%)	−189.7***	626.1	13,639	−155.1*	817.9	13,363	−34.5
Average Household size	−114.1*	686.2	15,180	−221.9***	765.6	11,822	107.8

Note: The table presents the Average Treatment Effect on the Treated (ATT) of the Cisterns Program on hospitalization rates due to acute diarrheal infections (ADI) for municipalities classified according to selected household water-management practices and infrastructure characteristics. For each classification parameter, municipalities are divided into above-average (a) and below-average (b) groups based on the corresponding indicator. ATT is estimated using the method proposed by Callaway and Sant'Anna (2021), with not-yet-treated municipalities serving as the control group. Classification variables are derived from the MDS beneficiary survey (for household practices among program participants). "Mean" denotes the average hospitalization rate due to ADI in the period *t-1* for the corresponding subsample, while *N* denotes the number of observations included in the estimation. ***p < 0.01, **p < 0.05, *p < 0.1.

7. Cost-benefit analysis

Considering the effects outlined in this study, it is useful to assess whether the benefits of the Cisterns Program justify its implementation costs (cf., Davis, 2009; Pattanayak et al., 2009). A conservative back-of-the-envelope cost–benefit analysis (CBA) suggests that they do. One of the program's main advantages is expanding access to safe drinking water for a large share of the population that would otherwise lack it. For many rural households, cisterns replace improvised sources such as small ponds and reservoirs, which are often contaminated and prone to drying during severe droughts (Castro, 2021). This explains the health benefits discussed here.

In addition, before the program, alternative water sources were often located far from households, requiring time-consuming and physically demanding tasks to fetch water. Gomes and Heller (2016) estimate that households spent an average of 2.4 h per day fetching water (36.7 days per year), a burden reduced by approximately 90% after program adoption. Similarly, Silva (2009) finds that nearly 60% of households spent 2 h daily collecting water. Cisterns enable households to harvest and store water, reducing physical strain – particularly for women and children – and freeing up time for productive activities such as education, paid work, or rest.[52]

Focusing only on these two benefits (health improvements and time savings[58]), the CBA indicates that the program would pay for itself within 14 years, generating a net present value equivalent to 36% of total program costs over a 20-year horizon.[53] The analysis assumes full program deployment in 2020, thereby avoiding assumptions related to gradual rollout, and expresses all costs in 2020 values.[54]

On the benefit side, the analysis uses the average treatment effects from 2020 (Table A25) to estimate averted hospitalizations and associated healthcare savings, factoring in the average duration of hospital stays due to ADI.[55] Additionally, the value of time saved by beneficiaries is calculated using the national minimum wage, with a conservative assumption that only 5% of the time saved from not fetching water or seeking medical care is converted into productive activities.[56] This intentionally cautious analysis suggests that the program's economic benefits outweigh its installation and operational costs within a reasonable timeframe. Given that cisterns are durable goods, designed to last at least 25 years, this finding provides reasonable assurance that the Cisterns Program generates tangible economic returns as a public policy.

8. Final remarks

Climate change is intensifying water insecurity and preventable disease in some of the world's most vulnerable regions. This study shows that a decentralized, low-cost intervention can substantially blunt these climate-related impacts.

Beyond average health improvements, these findings speak directly to the climate resilience literature, which emphasizes the capacity of systems to absorb and withstand shocks rather than solely improve mean outcomes. By expanding access to reliable household water storage, the Cisterns Program reduced hospitalizations due to acute diarrheal infections by 34% across Brazil's Semiarid Region. At the same time, the program does more than reduce disease incidence in normal years: it also alters the sensitivity of health outcomes to climatic stress. Empirically, access to cisterns eliminates or, at a minimum, sharply attenuates the marginal effect of drought shocks on waterborne disease. In this sense, the intervention reduces vulnerability by flattening the health-climate gradient, providing rare causal evidence that decentralized infrastructure can function as an effective resilience-building mechanism.

The Brazilian experience further suggests that these resilience gains emerge once program coverage reaches roughly 50% of estimated demand, offering a concrete and policy-relevant threshold for governments seeking to build climate resilience in other drought-prone regions facing similar shocks.

Importantly, the estimated effects should be interpreted as lower-bound impacts. The analysis relies on hospitalization data, which captures only the most severe cases of waterborne diseases, i.e., those requiring medical care at hospitals. However, a considerable proportion of individuals suffering from diarrheal diseases may not seek hospital-based treatment. Self-medication, visits to local health clinics, and the use of traditional remedies are widespread practices, particularly in rural or underserved areas, and are not captured in the administrative data used here (e.g., Fisher Walker and Black, 2010; Lamberti et al., 2012).[57] Additionally, cultural taboos or stigmas associated with diarrhea may contribute to underreporting or avoidance of formal care, especially among specific demographic groups (e.g., Goldman and Heuveline, 2000; Cairncross et al., 2010; Hulland et al., 2015). These behavioral and social factors could systematically attenuate the observable impacts when the outcome is measured solely in terms of avoided hospitalizations.

Furthermore, structural barriers such as transportation costs, lack of nearby health facilities, and overcrowded public hospitals may deter individuals from seeking care, particularly during times of drought or health system strain. In this context, hospitalization rates may reflect not only the incidence of disease but also access to healthcare services and decisions made under conditions of financial and logistical constraint. The empirical analysis has employed several strategies to account for these factors, such as controlling for investments in health, water, and sanitation at the municipal level. However, the reliance on administrative hospitalization data inherently limits the ability to capture milder or untreated cases, as well as those managed through informal or community-based care.

[52] For households without cisterns, time losses also include seeking medical care for oneself or a family member. This can range from a day spent traveling to the hospital to the full length of a hospitalization, as relatives usually remain with and care for the patient throughout the stay.

[53] see Section A17 for details.

[54] Projected costs incorporate the occasional use of water tankers during severe droughts (Cerqueira et al., 2017). The cost of a water tankers is estimated in approximately USD 117 (Da Mata et al., 2023). This cost is then weighted by the estimated number of households affected by drought each year, based on the frequency of past shocks.

[55] The estimated averted costs of hospitalization consider only the government's perspective. Estimations use publicly available data from the Brazilian Ministry of Health. This adds another layer of conservativeness to the analysis, as it excludes any out-of-pocket expenses families may incur on medications or related care.

[56] This low conversion rate accounts for potential overstatements of benefits (Ho et al., 2014).

[57] The Ministry of Health began publishing data on ambulatory visits to local clinics, including information on patients' municipality of residence, in 2008. However, these records largely lack information on the diseases prompting the visits, which prevents replicating the analysis at this level of service provision.

[58] Several ongoing studies indicate that the program may also affect a broader set of socioeconomic outcomes, including employment, income, and mortality. Preliminary evidence on these outcomes is reported, for example, in a series of evaluations commissioned by the Ministry of Regional Development and conducted by the Group for the Economic Evaluation of Public Policies (GAPPE/UFPE). The reports are available at: https://www.gov.br/mds/pt-br/acoes-e-programas/acesso-a-alimentos-e-a-agua/programa-cisternas/resultados-e-avaliacoes/estudos-e-avaliacoes (Accessed on 10 May 2026).

Consequently, improvements in health outcomes resulting from the Cisterns Program may be more substantial than what can be inferred from hospitalization data alone.

Despite these limitations, the evidence presented here demonstrates that decentralized, low-cost water interventions can yield substantial public health and climate adaptation benefits when large-scale infrastructure may not be feasible.

While the provision of water is a central mechanism, a substantial share of the program's success lies in its educational component. Training beneficiaries in water management improves their ability to use and safeguard this resource effectively, reinforcing the program's long-term impact. Strengthening this dimension could further improve outcomes, ensuring that access to water translates into sustained health and resilience gains.

Overall, the findings highlight the importance of scalable, low-cost interventions in addressing climate vulnerability and public health challenges. The Cisterns Program stands as a successful example of how decentralized adaptation strategies, rooted in local knowledge and participation, can deliver meaningful results, particularly in contexts where large infrastructure projects may not be viable.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marcelo S. O. Goncalves reports travel was provided by Center for Latin American and Caribbean Studies at Duke University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary Information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.jeem.2026.103350.

Data availability

Replication materials for this article, including the data, code, and variable documentation required to reproduce all results in the main text and online appendix, are available at https://doi.org/10.7910/DVN/WPRVNO.

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